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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY

A NEW METHOD OF IMPACT EXCITATION OF UNDAMPED ELECTRIC OSCILLATIONS AND THEIR ANALYSIS BY MEANS OF BRAUN TUBE OSCILLOGRAPHS.

By E. Leon Chaffee.

Presented by G. W. Pierce. Received July 11, 1911.

Introduction.

Electrical oscillations are at present of interest chiefly on account of their practical applications to radio-telegraphy and radio-telephony. The production and study of very rapid oscillations is also of intense theoretical interest, and the applications of oscillations in high frequency measurements and in research are of no small importance.

Previous to the last few years practically the only method of producing oscillations was by means of the disruptive discharge of a condenser across a comparatively long spark gap between metallic terminals in air. Under such conditions a train of damped oscillations is produced at each spark. The duration of these trains is very short in comparison with the interval of time between them. It is evident that such an intermittent and impulsive system is ill adapted to accurate electrical measurements; and for use in wireless telegraphy the system is noisy, inefficient, besides which the necessity of using high potentials increases the danger and the difficulty of insulation. For wireless telephony, where a regular and continuous radiation of power is necessary, the long spark method is absolutely useless.

In the last few years there have come into extensive use the short gap or quenched spark method, and the arc methods of producing electrical oscillations. These methods make use of the characteristics of very short spark gaps between large parallel metal surfaces, or the peculiar characteristics of certain forms of arcs. The advantages of these methods of generating oscillations lie in their greater efficiency, the absence of noise, the much greater regularity and continuity of the resulting oscillations, and the use of low potentials. The trains of oscillations either follow each other very closely or, as with the arc method, the oscillations are continuous with no intervals of inactivity.

For the purpose of this article it will be sufficient simply to mention and to classify the short gap and arc methods according to the characteristics of the resulting oscillations, and to designate the types by the names of their observers or discoverers. There are three such types, namely: the Duddell or singing arc oscillations; the Poulsen oscillations; and the Wien oscillations, or the so-called "Stosserregung."

The Duddell[1] oscillations are produced when a direct-current carbon arc in air is shunted by an oscillatory circuit. This method of producing oscillations is characterized by the fact that the arc always remains lighted, that is, the condenser current is at every instant less than the supply or main current. These oscillations are of small energy and limited in frequency to about 10,000 per second which fact renders them impracticable for radio-telegraphy.

The Poulsen[2] oscillations are produced by the Poulsen arc, which is essentially a Duddell arc between a water-cooled copper anode and a carbon cathode; this arc takes place in a magnetic field and in an atmosphere of some hydro-carbon gas. In this case the arc is extinguished at each oscillation, the condenser current at some instants being greater than the supply current. The Poulsen oscillations are much more intense than the Duddell type, and much higher frequencies can be attained; the energy, however, grows rapidly less as the frequency is increased. Frequencies of a million or more can be obtained but with small energy. Although the Poulsen oscillations are used in wireless signaling they have some disadvantages, such as low efficiency, and the characteristic change of wave length with changing arc length and arc current.

Under the head of Wien[3] oscillations fall those produced by the Lepel[4] arc, the Peukert[5] arc, etc. The generators for oscillations of this class consist of two or more very short gaps between large metallic surfaces separated by paper, or by a thin film of oil, and so mounted as to exclude the air. The gaps are connected in series and shunted by an oscillatory circuit similar to the arrangement for the other forms of generators. Loosely coupled to this primary circuit is a secondary circuit in which are induced the Wien oscillations. At each breaking-down of the gap a highly damped train of oscillations ensues, which produces in the secondary circuit the two ordinary coupling waves. During the interval between the ending of one primary train and the beginning of the next the secondary circuit oscillates in its own free period. Thus there are produced oscillations of three periods, the latter being of the most importance.

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[1] W. Duddell, Journ. Inst. Elect. Eng., **30**, 232 (1900).

[2] V. Poulsen, British Patent Specifications, 15,599 of 1903.

[3] Max Wien, Physik. Zeitsch., **11**, 76, Feb. 1, 1910.

[4] Lepel, Electrician (London), **63**, pp. 142, 157, 174, 345, 376 (1909); **64**, pp. 153, 386 (1909–10); G. W. Nasmyth, Phys. Rev., **32**, No. 1, 103 (1911).

[5] Peukert arc, Electrician (London), **64**, 361, 550.

All of the above mentioned methods for producing oscillations were tried without success by the author in an attempt to obtain oscillations of a frequency of more than 10^7 vibrations per second, and of sufficient regularity, continuity, and intensity for use in another investigation. After the failure of the then known methods, further experimentation produced the new oscillation gap and method which are to be studied in the following contribution. The method in some particulars closely resembles the Poulsen method, but in electrical action the system is quite different from any included in the three classes mentioned above.

The oscillations of this new system do not fall in any of the three classes of oscillations mentioned, but are, as will appear later, intermediate between the Poulsen and Wien types. The oscillations produced are unlike the Poulsen oscillations in that their period is but very slightly affected by changes of supply current and not at all by changes of arc length, and they are sinusoidal in wave form. The oscillations are different from the Wien type in being continuous, and having but one period, which is practically the free period of the circuit in which the oscillations are induced.

It is shown in the following article that this new system produces oscillations superior to the other systems in regularity, which, with its simplicity, commends its use in the laboratory and in practice. It is the only method known by the author for producing intense continuous oscillations at extremely high frequencies. The author has obtained continuous and practically undamped oscillations of several amperes at 20 meters wave length, which corresponds to a frequency of 1.5×10^7 oscillations per second.

The following article is presented in three parts. In Part I it is proposed to give the general characteristics of the oscillation gap. In Part II the oscillations are studied more in detail by means of Braun tube oscillographs, and Part III contains a few practical considerations and applications of the oscillations.

PART I.

THE GENERAL CHARACTERISTICS OF THE OSCILLATION GAP.

(1) *Description of Apparatus.*

The gap consists essentially of an aluminum cathode and an anode of some other metal such as copper or silver, both water or air cooled and surrounded by an atmosphere of moist hydrogen. The active surfaces of the terminals are accurately parallel planes of one or two square centimeters area, and adjustable as to distance separating them, which, for the best results, is about .07 mm. Large terminals are undesirable on account of the increased electrostatic capacity of the gap, which must be small in comparison with the main capacity of the circuit.

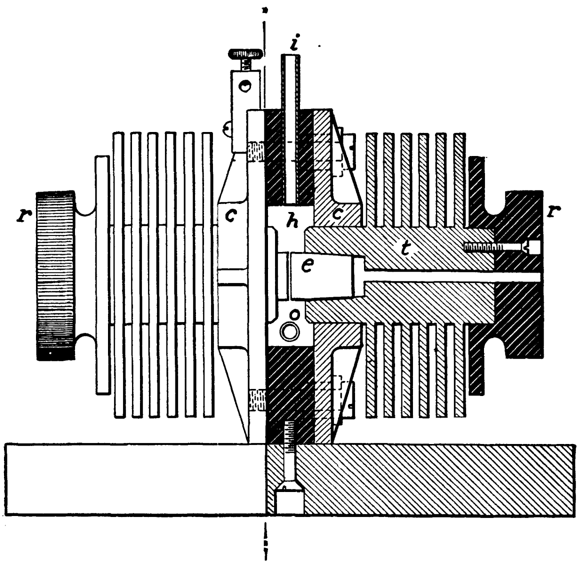

FIGURE 1. Air-cooled *Cu-Al* Discharge Gap. ½ natural size.

For the cathode, aluminum is the only metal which gives at all satisfactory results, and the gap should be constructed so that the terminals can be occasionally renewed. After the gap has been in operation for some time the aluminum becomes pitted and covered with a very hard oxide which is difficult to remove. One electrode was operated, however, for over one hundred hours with fairly satisfactory results at the expiration of that time.

Several metals work well as anode, the latter apparently playing very little part in the action of the gap. It appears, however, that the denser metals of high cathode drop, such as copper and silver, are desirable. The anode, with occasional cleaning, will serve indefinitely.

Although the amount of heat produced in the gap is small, some method of cooling the terminals is necessary. Air cooling by means of radiating vanes is to be preferred on account of convenience and simplicity. Figure 1 gives the details of an air-cooled gap, the right-hand half in section. At *e* there is shown the *Al* electrode which is held by a taper-fit in the massive terminal *t*. Opposed to this *Al* electrode is a similarly shaped copper electrode held by taper-fit in a similar massive terminal. These terminals are threaded and engage in the side castings *c c*, and are provided with blackened metallic radiating vanes as shown. The side castings are separated by a thin slab of hard rubber or asbestos board, which has a central circular hole to serve for the gap chamber *h*. Rubber handles *r r* are for use in adjustment. The inlet and outlet for the hydrogen are shown at *i* and *o*. The drawing is one half size.

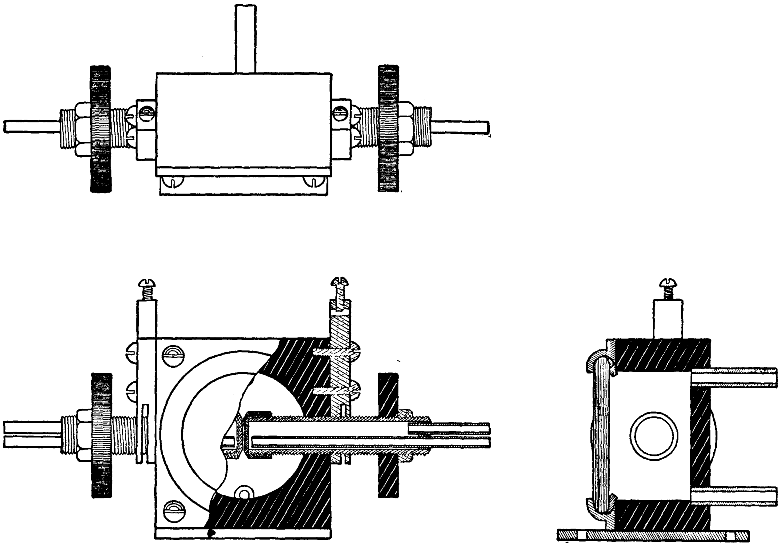

FIGURE 2. Details of Water-cooled *Cu-Al* Gap. $\frac{2}{5}$ natural size.

A water-cooled gap as shown in Figure 2 was, however, used throughout this investigation. By reference to the drawing this gap is seen to consist of two hollow threaded electrodes capped with aluminum and copper, respectively, and each provided at the outside end with an inlet and outlet tube for the passage of the cooling water. The terminals are enclosed in a hard rubber casing provided with a circular glass front. Hard rubber disks attached to the electrodes serve for adjusting handles. The figure is a reduction in the ratio of 5 to 2.

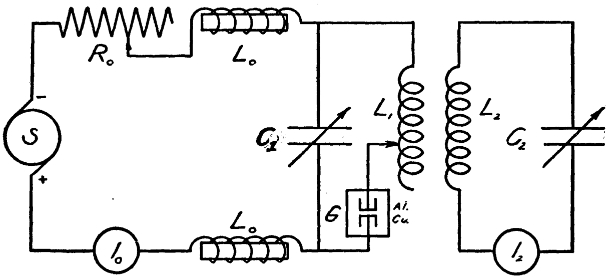

FIGURE 3. Diagram of Connections.

The general diagram of connections is shown in Figure 3. S is a source of direct current of a few hundred volts, and, in what follows, 530 is to be assumed unless otherwise stated. I_0 is a D. C. ammeter which measures the current in the supply circuit. This circuit also contains the two inductances or choke coils L_0 L_0, and a variable resistance R_0, capable of reducing the current to about 0.2 ampere. In the following experiments L_0 L_0 are ordinary A. C. arc-light inductances, and R_0 is a resistance, adjustable in one half ampere steps, in series with a variable copper-sulphate electrolytic resistance. C_1 and C_2 are variable air condensers, G the gap, L_1 and L_2 the variable primary and secondary of the closely-coupled oscillation transformer, and I_2 a hot-wire ammeter.

(2) *Operation of Gap.*

The system will start automatically if the distance between the terminals is not much greater than 0.1 mm. In appearance the discharge resembles a very minute arc, of an intense reddish-purple color, absolutely quiet and stationary. The discharge remains at one point on the electrodes for several minutes until the aluminum is slightly pitted, when it suddenly shifts to another point. When the discharge is examined by means of a spectroscope only the primary hydrogen spectrum appears with an occasional weak flashing-up of a few of the aluminum lines. Plate 1*b* gives the discharge spectrum with an aluminum comparison spectrum. The nature of the discharge will be considered more in detail in Part II, but it is evident from the figure that the metals are not vaporized, and the indications are that the conduction is entirely by gaseous ionization.

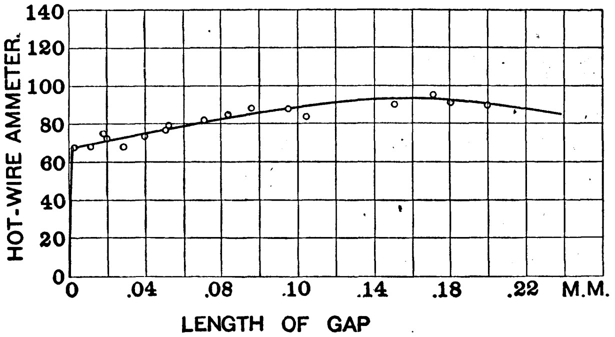

Figure 4. Effect of Changing Length of Gap.

I_0 = .335 ampere.
λ_2 = 106 meters.
$C_1 = 112 \times 10^{-5}$ μ.f.
$C_2 = 60 \times 10^{-5}$ μ.f.

When the secondary oscillations are examined by means of a wave meter, but one wave with exceedingly sharp tuning is observed. On account of the steadiness of the oscilliations it is often difficult to set the wave meter — which makes use of a telephone receiver as the detecting device — without the use of a chopper or interrupter in the wave meter circuit.

The change in wave length of the secondary oscillations with changing supply current is very much less than is observed with the Poulsen and Lepel generators. This point is, however, more profitably considered later, after a better understanding of the action of the gap has been gained.

In order to show the effect on the intensity of the secondary oscillations of varying the length of the gap, the curve shown in Figure 4 was taken. It is seen that the intensity of the secondary current, as measured by the hot-wire ammeter, does, to some extent, depend upon the length of the gap, but not to the extent that might be expected. At 0.19 mm. the secondary current is a maximum, but at about this length of the gap the discharge begins to hiss and become unsteady. For other values of the main current, I_o, the curve would be slightly different, but, in general, the best results are obtained with a gap length of from .04 to .09 mm.

The effect of changing the pressure of the hydrogen was investigated. Apparently atmospheric pressure gives the most satisfactory results, although, for decreased pressure, the oscillations are possibly slightly more intense until the pressure of about 10 or 20 cm. is reached, when they rapidly become weaker. Increased pressure is decidedly detrimental.

Before entering upon an explanation of the curves and results it is essential that a comprehensive idea of the operation of the system be had. To this end the following brief review of the events during one cycle is introduced, the details of which will be considered more at length later. It is clearest, in tracing the sequence of phenomena, to begin at the instant after the system has been started, when the potential of the primary condenser C_1 (Figure 3) has attained a value sufficient to break down the high resistance of the gap. The gap resistance rapidly falls to a very low value as the discharge of condenser C_1 and the main current I_o, which was previously flowing into C_1 and which remains practically constant on account of the inductances L_o L_o, rush across the gap and through the primary coil L_1. This current rush takes place according to a definite positive loop of current with respect to time, the shape, amplitude, and duration of which depend upon the constants of the circuit, the rapidity of absorption of energy by the secondary circuit, and, to a slight extent, upon the conditions of the gap and strength of the main current I_o. The condenser C_1 is discharged and charged somewhat in the opposite direction by this positive current rush. If conditions are right the discharge stops as soon as I_1 becomes zero, there being no inverse current. The secondary receives a certain increment of energy from this discharge, and continues to oscillate after the primary discharge stops.

This absence of inverse current above referred to is due to the combination of three conditions. First, and most important, is the practically instantaneous re-establishment of the high initial gap resistance when the current becomes zero, due probably to the formation of an insulating oxide film on the aluminum; second, the higher cathode drop of the anode metal; third, the absorption of energy by the secondary, although rectification usually takes place without this aid.

At the end of the above mentioned current-rush the current through the gap is zero and the condenser C_1 has an inverse charge. Since the main current must remain constant it is now flowing into C_1, it having been gradually shifted over to C_1 as I_1 decreased toward zero. The main current I_0 flows into C_1 at a practically constant rate, neutralizing the inverse charge and charging it in the initial direction. The potential difference of C_1 increases uniformly, attaining a much higher value than exists outside the choke coils.

Impressed across the gap is the potential difference of the condenser C_1 plus the ripples induced in the primary circuit by the secondary current, these potential ripples serving as a trigger to start the primary discharge on a second cycle in the proper phase relation with the secondary oscillation.

It is evident from the above consideration that, on account of the inductances L_0 L_0, the condenser C_1 can attain a much higher difference of potential than that of the source, the magnitude of this condenser potential being determined by the breaking-down potential of the gap. It is also clear that, if this breaking-down potential be assumed approximately constant, the number of discharges of C_1 per second depends upon the main current I_0.

The duration of each primary discharge does not, as has been stated, depend upon the supply current, so that it is only the duration of the interval between primary discharges which changes with varying main current. The secondary continues to oscillate during these intervals with decreasing amplitude according to the damping of the secondary circuit. In what follows the number of secondary oscillations to one primary discharge and charge is spoken of as the "inverse charge frequency referred to the secondary oscillation" or simply I. C. F.

From what has been said it is clear that the secondary receives periodic impulses from the primary, the frequency of these impulses depending upon the main current and the capacity of the primary condenser. During the intervals of non-activity of the primary circuit the secondary circuit oscillates in its own free period and with damping determined solely by the conditions of the secondary circuit, such as resistance and radiation. The secondary oscillation cannot, then, strictly be called undamped. The amplitude of the oscillation can, however, be maintained practically constant by making the primary impulses occur every two or three secondary oscillations, and, if the damping in the secondary circuit be small, the resulting oscillations are then almost perfectly undamped and continuous.

In order that the maximum energy be transferred to the secondary circuit there are two conditions of syntony, as they may be termed, to be fulfilled. In the first place the primary discharges must always occur in the proper phase relation with the secondary oscillation, or, in other words, the I. C. F. must be a whole number. This is, as has been pointed out, more or less automatically regulated by the reaction of the secondary oscillation on the primary circuit, but not entirely so for low values of I. C. F. The second condition of syntony is that the *shape* of the primary wave or current-rush must be such that the resulting electromotive force impulses in the secondary circuit, due to the different parts of the primary wave, bear the proper phase relation to the secondary wave. With a fixed secondary circuit the first condition can be obtained by varying the main current I_0, or the primary capacity C_1. The second condition of syntony can be established by changing the primary inductance L_1.

(3) *Observations and Discussion of Results.*

The two conditions of syntony are illustrated by the curves of Figures 5 and 6. In Figure 5 the full line curve gives the variations of the secondary current, I_2, plotted to an arbitrary scale, as the main current, I_0, is varied, and shows maxima and minima of I_2 as the first condition of syntony is more or less perfectly fulfilled. The dotted disconnected lines give the maximum wave length readings of the wave meter, excited by the primary discharge, as ordinates plotted to the variable I_0. The third dot-and-dash curve is the wave meter reading when the secondary circuit is open. This figure is a fair representation of several curves taken under different but similar conditions.

In explanation of Figure 5 attention is called to the following facts. It is evident that if the potential to which the condenser is charged is practically the same under all conditions, — and experiment shows that this is approximately the case,— then with a given C_1, the number of discharges per second in the primary circuit is roughly proportional to the current I_0. This actual spark frequency produces in the wave meter an effect corresponding to a wave of that frequency. This primary fundamental wave length, as it will be called, plotted to I_0 would give a curve of the general shape given by the dot-and-dash line in the figure. When, however, the secondary circuit is closed the secondary current exerts an equilibrating influence on the primary discharge, helping it to occur, as has been stated, at a definite time in relation to the secondary current, thereby forcing the primary circuit to operate according to the short horizontal lines. For instance, by reference to the figure it is seen that, for a supply current of 0.7 ampere, the unforced primary fundamental wave length is 350 meters. The frequency corresponding to this is about 860,000 per second, which means that there are that number of primary discharges occurring per second. When, however, the secondary circuit, having a natural wave length

$\lambda_2 = 95$ metres, is closed, conditions are different on account of the absorption of energy by the secondary circuit, and the primary discharges at a rate corresponding to a wave length of about 280 meters. This is about three times λ_2, showing that the I. C. F. is 3. As the supply current is decreased the primary is forced by the secondary to discharge at this rate until the current has become so small that the slower rates corresponding to I. C. F.'s of 4 or 5 are more stable. When conditions are least forced for these values of I. C. F. a maximum of secondary current is observed as shown at $I_0 = 0.46$ in the figure. It is seen that for the steep part of the dot-and-dash curve the I. C. F. jumps between several successive values. It is also now easy to understand that the maxima of secondary current naturally occur at values of I_0 where the I. C. F. is less forced.

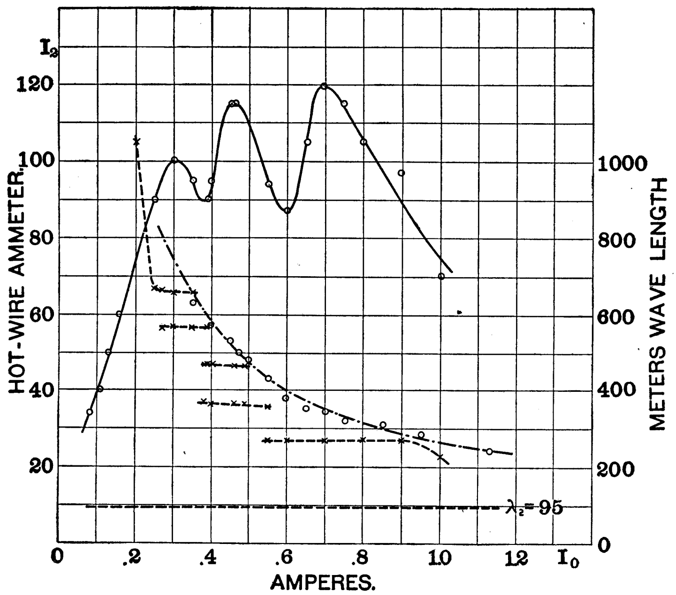

FIGURE 5. Illustration of Syntony to Charge Frequency.

$\lambda_2 = 95$ meters.
$C_1 = 80 \times 10^{-5}$ $\mu.f.$
$C_2 = 60 \times 10^{-5}$ $\mu.f.$

The second condition of syntony, namely, the syntony of wave form, is represented in Figure 6. In this case the hot-wire ammeter reading was taken in the secondary circuit as an inductance, in series with the primary of the oscillation transformer, was varied, the abscissa scale being in turns of the coil. The disconnected curve, marked λ_1, represents the primary fundamental wave length plotted to turns of inductance.

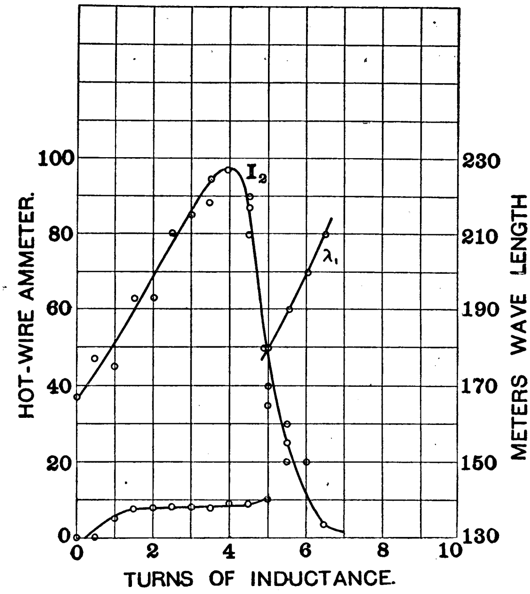

Figure 6. Curve showing Syntony to Wave Form.

λ_2 = 86 meters.
I_0 = .75 ampere.
$C_1 = 60 \times 10^{-5}$ $\mu.f.$
$C_2 = 40 \times 10^{-5}$ $\mu.f.$

The curve of secondary current shows the marked maximum when, the I. C. F. remaining constant, the primary discharge loop has the best duration compared to the period of the secondary oscillation. The forcing by the secondary oscillation of the primary to discharge at the frequency corresponding to a wave length of 138 meters is well shown by the λ_1 curve.

A very interesting and useful chart, in showing the way in which the variables change, is shown in Figure 7. This diagram was taken for

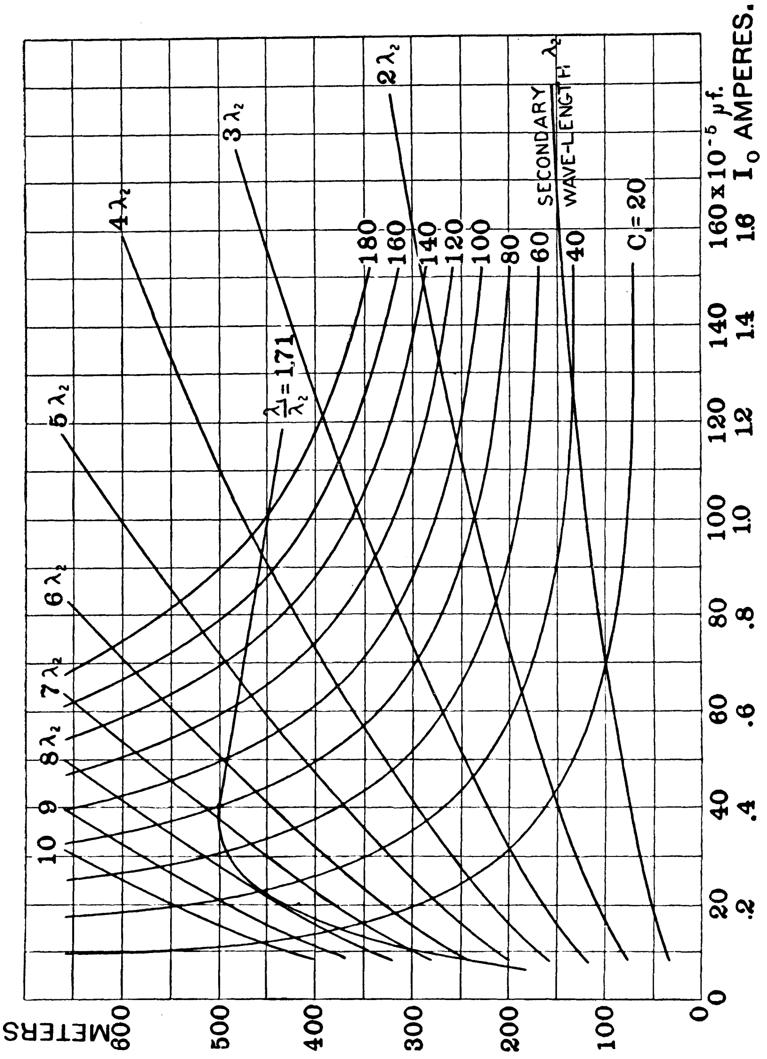

FIGURE 7. Experimental Chart.

particular values of L_1, L_2 and the coefficient of coupling of the two circuits, and is not general so far as the scales are concerned. The shape of the curves is general, however, and, it is hoped, may prove explanatory of the relations of the many variables.

The curves resembling hyperbolas are each for a constant primary capacity plotted with main current, I_o, as abscissae, and fundamental wave length of the primary discharge frequency as ordinates. The lower curve, marked "secondary wave length," gives the capacity of the secondary circuit as abscissae and the resulting syntonic secondary wave length as ordinates. The other similar curves are got by multiplying the ordinates of the last-mentioned curve by 2, 3, 4, etc. The remaining curve marked $\frac{\lambda_1}{\lambda_2} = 1.71$, needs a word of explanation. Several measurements were taken of the natural period of the primary circuit when adjusted to give maximum secondary current, for different secondary wave lengths, and it was found that this natural primary period divided by the corresponding secondary period was, in every case, within one or two per cent of the quantity 1.71. This would be slightly different for different coefficients of coupling. The curve in question is the locus of the intersections of the vertical C_2 lines and the C_1 curves which fulfill this condition.

The use of the diagram of Figure 7 may be made clearer by the following. Suppose that the secondary wave length desired is 75 meters. The secondary wave length curve gives $40 \times 10^{-5} \mu.f.$ as the secondary capacity, and passing vertically up to the $\frac{\lambda_1}{\lambda_2}$ curve, it is seen that the primary capacity must be $80 \times 10^{-5} \mu.f.$ If, now, the vertical $C_2 = 40$ line be followed to the intersection of the $3\lambda_2$ curve, and then horizontally to the same $C_1 = 80$ curve, and down to the current axis, one gets the current $I_o = 1.1$. This current gives the discharge frequency, with $C_2 = 80$, corresponding to a wave length of 225 meters, which is three times the secondary wave length, and therefore shows that, with that I_o, the primary condenser is discharging every third secondary oscillation. In other words, the I. C. F. is 3. Similarly it is seen that for an I. C. F. of 4 the main current must be 0.69 amperes; for I. C. F. equal to 5, I_o must be 0.54 amperes, etc.

Among other things the diagram shows that in general the supply currents which give the large values of I. C. F. differ but slightly, which is an advantage for some purposes. It is readily seen that small values of I. C. F. are impossible to obtain unless the wave length is short and the supply current very large.

The coupling between the primary and secondary circuits should be very close. In order to attain this the primary and secondary coils were wound parallel on the same frame so that they interlocked. The diameter of the coils is about 5 inches, and from one to seven or eight turns were used. Direct coupling is almost as satisfactory as magnetic coupling, but for regularity and freedom from harmonics the latter is to be preferred, and was used throughout this experiment. The closeness of the coupling, or, what is of more importance, the mutual inductance between the primary and secondary circuits, should, for the best results, be adjusted according to the amount of power delivered by the secondary circuit. The connection between the mutual inductance and the conditions in the secondary circuit is shown by the curves of Figures 8, 9 and 10.

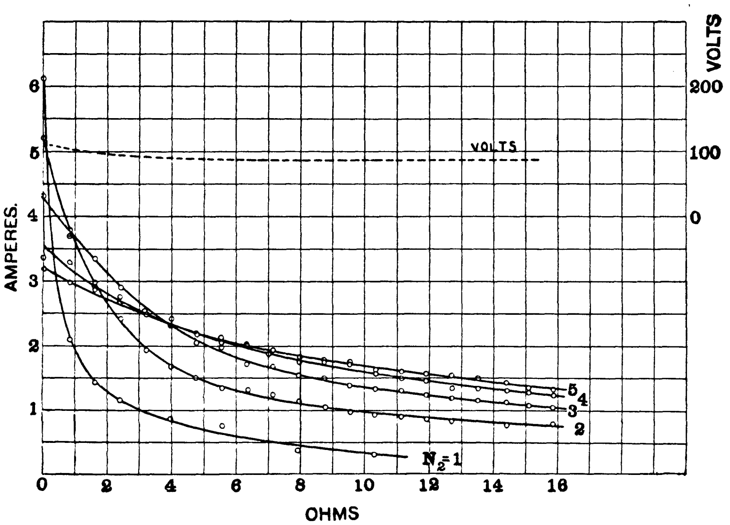

FIGURE 8. Current Curves, with Changing Resistance.

$\lambda = 100$ meters.
$I_0 = .55$ ampere.
$C_1 = 175 \times 10^{-5}$ $\mu.f.$
$C_2 = 86 \times 10^{-5}$ $\mu.f.$

In taking the curves of Figure 8, the primary supply current, the primary capacity, and the secondary wave length were kept the same in order to maintain constant the two syntony conditions, while a resistance in the secondary circuit was varied for different numbers of turns on the secondary helix. The primary capacity was 175×10^{-5} $\mu.f.$;

the supply current was 0.55 ampere, and there were four turns on the primary helix. The secondary wave length was 100 meters and the curves 1–5 give the values of I_2 in amperes for the designated number of turns on the secondary coil, as the resistance in the secondary circuit was varied from 0 to 16 ohms. On the same diagram appears the voltage across the gap for the several conditions.

These, and some of the curves shortly to be considered, are plotted for, or in terms of, turns of secondary helix, the primary helix remaining unchanged. With the apparatus used the mutual inductance between the two circuits is not exactly proportional to the number of secondary turns on account of a slight variation in the position of the coils, but nearly enough so, so that the number of secondary turns can be considered as proportional to the mutual inductance between the primary and secondary circuits.

The resistance used in the secondary circuit was an oil-cooled manganin wire resistance, wound non-inductively, and with a wire of such a diameter that the high frequency resistance is considered to be practically the same as the ordinary resistance.

It is clear, on examination of the current curves of Figure 8, that if a large current in a circuit of small resistance is desired, the mutual inductance should be small. If, on the other hand, there is a considerable radiation of power from the secondary circuit, or if the circuit contains a large resistance, it is necessary that the mutual inductance be large.

The reason for this necessary change in mutual inductance to suit the various conditions is to be sought in the reaction of the secondary current on the primary circuit. It is probable that the coupling should be as close as possible consistent with a certain reaction, above which the primary conditions, such as phase, etc., would be affected to the extent of causing the power to decrease. Suppose then it be assumed that the *permissible* reaction on the primary is constant, and that the current in the secondary is proportional to M, the coefficient of mutual inductance. Then it follows that the reaction voltage, E_1, in the primary is

$$E_1 = \text{const.} \propto MI_2.$$

But $I_2 \propto \frac{M}{R_2}$ if the wave length and primary current are constant.

Therefore

$$E_1 \propto \frac{M}{R_2} = \text{const., or } M^2 \propto R_2.$$

If, now, M be assumed proportional to N_2 the above expression may be written,

$$N_2^2 = KR_2, \text{ where } K \text{ is a constant.}$$

This is the relation which must probably approximately hold in order that the reaction of the secondary current on the primary circuit may not exceed a certain amount, and is, therefore, for a given R_2 or radiation coefficient of the secondary circuit, the condition for maximum power. This will later be shown experimentally to be nearly true.

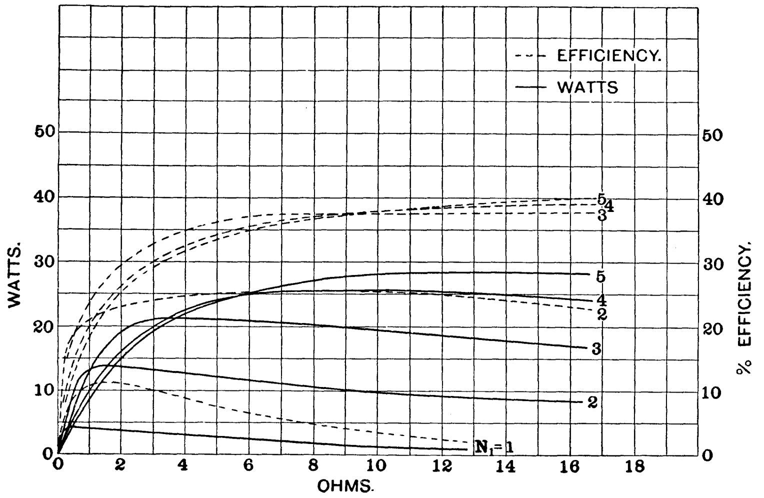

Figure 9. Power and Efficiency Curves with Changing Resistance.

λ_2 = 100 meters.
I_0 = .55 ampere.
$C_1 = 175 \times 10^{-5}$ $\mu.f.$
$C_2 = 86 \times 10^{-5}$ $\mu.f.$

In Figure 9 is plotted the power, $I_2^2R_2$, in watts dissipated in the secondary resistance for the conditions represented in Figure 8, from which the curves of Figure 9 were obtained, and, also, the corresponding efficiencies (dotted lines) exclusive of the power lost in the outside resistance, R_0, are shown. The heat lost in R_0 is omitted in calculating the efficiencies because, as will be stated later, by a proper choice of generator this resistance can be left out.

The full line curves of Figure 10 were derived from those of Figure 8, and are constant secondary current curves plotted to the ratio of secondary to primary turns of helix as ordinates, and secondary resistance as abscissae. The ordinate scale is, as has been pointed out, practically proportional to the mutual inductance between the two circuits, but, for the sake of definite units, is expressed in terms of turns of helix. The curves were derived by taking the intersections of the horizontal, 1, 1.5, 2, 3, 4, and 5 ampere coördinate lines with the secondary current curves of Figure 8, and plotting to the corresponding secondary resistances. The dot-and-dash curve is drawn through the points of maximum slope of the constant current curves, and is the locus of the points representing maximum power output. It is approximately a parabola, expressible in the form

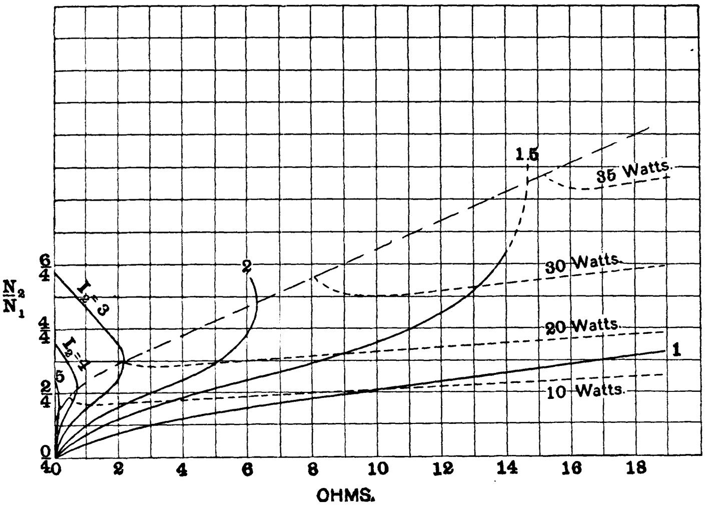

FIGURE 10. Power Curves Derived from Figure 8.

$\lambda_2 = 100$ meters.
$I_o = .55$ ampere.
$C_1 = 175 \times 10^{-5}\ \mu.f.$
$C_2 = 86 \times 10^{-5}\ \mu.f.$

$$\left(\frac{N_2}{N_1}\right)^2 \propto R_2, \text{ or, since } N_1 = 4 = \text{const.},$$

$$N_2{}^2 = K_1 R_2 \text{ where } K_1 \text{ is a constant.}$$

This is the same expression which was previously derived by assuming the existence of a maximum permissible reaction of the secondary current on the primary circuit, and shows that, within the errors of experiment, the assumption is fairly well borne out.

The remaining dotted curves of Figure 10 are calculated constant-watt curves, and enable one to tell at once the power being delivered under any condition represented by the full line curves of the diagram. Apparently the larger the secondary resistance and the greater the number of turns on the secondary of the helix, the greater would be the power output, but it will be seen that the distance between the constant-watt curves rapidly increases, making it necessary to very much increase R_2 and N_2 to give a slightly larger output. Therefore the curves do show the existence of a limit to the power derivable from one gap. These curves also show that with a small number of turns on the secondary helix it is impossible to deliver to the secondary a large amount of power no matter what the resistance is in the secondary circuit. It is clear, as has been said before, that the mutual inductance must be large, and the radiation or resistance large in order to obtain a large amount of power from the secondary circuit.

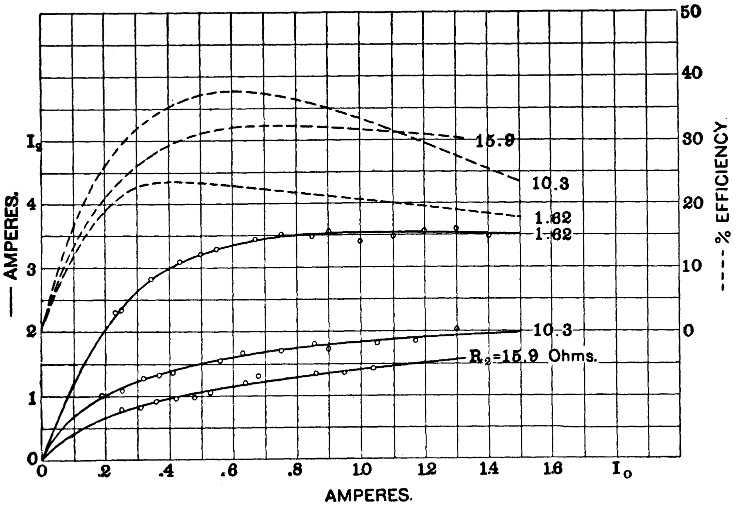

FIGURE 11. Power and Efficiency Curves with Changing Current, [I_0].
$\lambda_2 = 100$ meters.
$C_1 = 175 \times 10^{-5}\ \mu.f.$
$C_2 = 86 \times 10^{-5}\ \mu.f.$

The curves of Figure 8 and those of Figures 9 and 10, which were derived from Figure 8, were taken when the supply current, I_0, was maintained constant at .55 amperes, the current which, with a wave length of 100 meters, gives about the best average efficiency for all conditions. The curves of Figure 11 show the effect on the efficiency of changing the supply current, I_0. The secondary wave length was maintained constant at 100 meters, and there were 4 turns on both the secondary and primary of the helix. The full line curves show the variations in current in amperes in the secondary circuit for three values of secondary resistance, as the main supply current, I_0, is varied from 0 to 1.5 amperes. The dotted curves give the efficiencies for the three curves plotted to the right hand scale. The relative magnitudes of the efficiencies would be slightly different for other values of $\frac{N_2}{N_1}$, but the curves show that for 100 meters wave length in the secondary, the maximum efficiency is obtained when the gap is operated on a supply current of from 0.3 to 0.8 ampere, the exact magnitude of the supply current for maximum efficiency depending on the resistance in the secondary circuit.

All of the data given above are for a wave length of 100 meters in the secondary circuit. The shape of the curves would be similar for other wave lengths but the scales different. If the secondary wave length were longer the primary condenser would be larger, and the supply current for maximum efficiency would be greater, but the gap does not work steadily under any conditions with a supply current greater than about 1.5 amperes.

In conclusion of Part I, a few words should be said concerning the variation in frequency of the secondary oscillations as the supply current is changed. Although this point has not as yet been investigated at all thoroughly, the conclusions drawn from some experiments and observations show that the frequency of the oscillations increases slightly, and practically linearly, as the supply current is increased. This increase is from 1 per cent to 10 or 12 per cent for a change of supply current from .2 to 2 amperes, and depends upon the adjustments, the percentage increase being greater the closer the coupling, and the greater the number of primary discharges per second.

It is improbable that this change in frequency with changing supply current can be attributed, as is done in the case of the Poulsen and Lepel arcs, to the change in slope of the voltage-current characteristic, for a change in gap length, which changes the slope of the E-I curve more than a change in supply current, does not cause a detectable change in frequency. If there is a change in frequency due to change of gap length, it is less than 1 per cent for a change of gap length from .005 to 0.15 mm.

It is thought that the variation of frequency with changing supply current is due to a wavering or shifting of the period of the secondary oscillation between a forced condition, when the primary is in action, and the free period of the secondary circuit, when unaffected by the primary discharge, this wavering being more often and of a greater effect on the resultant or average wave length the greater the number of primary discharges per second. The number of primary discharges is proportional to the supply current, so that according to the above assumption, the change in frequency would be directly proportional to the supply current.

The large changes in frequency with changing arc current and arc length is a serious disadvantage in the use of the Poulsen arc, but with the system being studied, the change of frequency is so small and the supply current and arc length remain so very constant that there is, under all ordinary circumstances, practically *no* change in frequency.

PART II.

ANALYSIS OF OSCILLATIONS BY MEANS OF BRAUN TUBE OSCILLOGRAPHS.

In Part I the general characteristics of the aluminum-cathode oscillation gap were studied, but little idea could be obtained as to the instantaneous relations of the variables. It is the purpose in Part II to analyse, by means of the Braun cathode-ray tube, the entire sequence of events during a complete cycle of changes, and to develop a clearer idea of the nature of the oscillations and the action of the gap. Before attacking the problem, however, it is necessary to describe the additional apparatus made use of in the following experiments :

(1) *The Braun Tubes and Accessory Apparatus.*

The Braun cathode-ray tube is a most valuable piece of apparatus for delineating transient electrical phenomena. Its use has been described by Braun,[6] Zenneck,[7] and others,[8] but a few words from the author's experience with the use of the Braun tube in connection with high frequency currents may be of interest.

The Braun tubes used in the following work were imported from Germany, but it was found necessary to alter them. The aluminum or mica diaphragms, which serve to limit the cathode stream to a small pencil, were replaced by glass diaphragms, sealed into the tubes and having the shape of a truncated cone. The apertures of the diaphragms are from .5 to .7 mm. in diameter, and give a very sharply defined luminous spot of about 1 to 1.5 mm. diameter on the fluorescent screen. Figure 12 shows the general form of the tubes and the glass diaphragms.

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[6] F. Braun, Wied. Ann., **60**, 552 (1897) ; Elektrot. Ztschr., **19**, 204 (1898).

[7] Zenneck, Ann. d. Physik., **9**, 497 (1902).

[8] J. M. Varley, Phil. Mag., **3**, 500 (1902) ; Varley and Murdock, Electrician (London), **55**, 335 (1905).

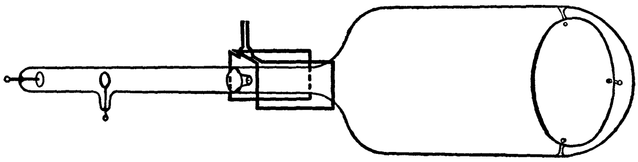

FIGURE 12. Braun Tube and Deflecting Coil.

Braun tubes making use of electrostatic deflection of the cathode beam were also used in parts of the experiment. They are essentially the same as those just described with the addition of the two electrostatic deflecting plates. These plates are about 8 by 2.5 cm. in dimensions, and are sealed inside the tubes about 2.5 cm. apart.

Several Braun tubes have been made at the laboratory, and it was found important that the distance between the cathode and the anode should not be less than about 15 cm. A very sensitive fluorescent screen for visual observation is made by dusting very finely powdered willemite over a piece of mica or glass freshly painted with a thin coat of water glass, although according to Zenneck a zinc sulphide screen is to be preferred for photography and was used in this research.

In order that the cathode beam may be homogeneous, that is, have at all times the same velocity and consequently the same deflection under a certain force, it is necessary that the potential of the source causing the discharge be very constant. This restriction, of course, excludes induction coils and transformers, and practically limits the desirable sources to either the large static machine or the high potential battery.

If a static machine is used, one of many plates is necessary in order to give sufficient intensity to the cathode beam, and if possible the plates should have no sectors or carriers.

The ideal source of current for a Braun tube is the high-voltage secondary battery, capable of giving a potential of from 10,000 to 20,000 volts. In order to control the current, should the vacuum drop, the current from such a plant should pass through two or three feet of running water in glass tubes. In this investigation the Braun tubes were operated on Professor Trowbridge's large 20,000 cell battery, which has proved of the greatest value in this and other work. Usually not over 20,000 volts were used, that being sufficient, under proper adjustment of vacuum, to give a very intense and homogeneous cathode beam.

The proper adjustment of the vacuum is of the utmost importance, and depends entirely upon conditions. For the greatest intensity of the spot and, at the same time, the greatest sensitiveness, the pressure inside the tube should be as high as possible consistent with a clearly defined spot. After some experience, the appearance of the discharge about the cathode serves as the best indicator as to the exhaustion. The best results are usually obtained when the luminous stream from the center of the cathode is about 1 mm. in diameter, although in special cases a higher or perhaps a lower exhaustion is desirable. The vacuum, however, changes when using large currents, making it necessary that the tubes be in connection with a mercury pump. The Gaede rotary pump was used in this investigation.

If a pump in connection with the tube is not convenient, a vacuum regulator, containing potassium chlorate or some other substance such as is used on X-ray bulbs, is suggested for lowering the vacuum when necessary.

In order to eliminate the deflection of the beam by the earth's magnetic field, the tubes are mounted with their axes parallel to the earth's magnetic force, which mounting gives the tubes an inclination of about 70° with the horizontal. The camera, for photographing the oscillographs, was directed downward, viewing the upper or front surface of the fluorescent screen. Plate **1** *a*, shows the general arrangement of apparatus.

The deflecting coils, when used with high frequency current, can, of course, contain no iron. The coils, which were used in this investigation for the magnetic deflection of the cathode beam, are composed of from two to sixteen rectangular turns of copper wire, .325 cm. in diameter, half of the turns being on either side of the tube. The turns are about 7 or 8 cm. in width, and from 10 to 12 cm. in length. A nearly uniform field within the coil is secured by making the width of the rectangular turns $\sqrt{2}$ times the distance between the planes of the two parts of the coil.

When using high frequencies, the difference in potential between two parts of the same coil, due to inductance, is sufficient to cause very large electrostatic deflections of the cathode beam. This disturbance is most effectually eliminated by surrounding the tube inside the coil by a split solenoid of fine insulated copper wire wound on a paper tube. This device completely shields the cathode beam from electrostatic disturbances, but allows the magnetic forces to pass undiminished.

When the Braun tube is used for alternating currents of commercial frequencies, or for phenomena taking place in a few hundredths of a second, the velocity of the luminous spot over the screen is small enough to give a visible streak of light even if the phenomenon lasts for only one cycle.

When high frequency currents are used, however, the velocity of deflection of the cathode beam is so great that it is necessary that the luminous spot travel over the same path thousands of times a second in order that even a visible effect may be observed, and many more times if a photographic record is to be taken with a reasonable exposure.

It is then apparent that, if a sequence of instantaneous phenomena is to be delineated by causing the cathode beam to trace out a pattern on the fluorescent screen of the Braun tube, the cycle of events must repeat many hundreds of thousands of times a second, and with such regularity that the spot of light will, each cycle, travel over exactly the same path.

When using the Braun tube for studying electrical oscillation, this is usually more or less of a difficult condition to attain on account of the uncertain and variable action of most forms of discharge gaps. The gap and system under consideration is, however, so regular and constant that it is not at all difficult to obtain photographs of patterns representing cyclic changes, many of which recur three million times a second with practically no variation.

Plates 1–7 are a few of over fifteen dozen photographs taken representing various conditions, and give unmistakable evidence of the remarkable regularity and continuity of the oscillations of the *Cu-Al* gap. The photographs were taken on Seed's Gilt Edge No. 27 plates, and exposures of from 3 to 30 seconds were made. The figures are practically natural size.

(2) *The Primary Wave.*

The observations for determining the shape and phase, with respect to the secondary oscillation, of the primary current rush were obtained by leading the primary and secondary currents each through a 4-turn deflecting coil about the Braun tube, the two coils making an angle of 90° with each other. The arrangement is diagrammatically shown in Figure 13, where the letters have the before mentioned significance.

There is obtained on the fluorescent screen by this arrangement a perfectly definite and well defined pattern, which gives the corresponding instantaneous values of the primary and secondary currents. Plate 1 *c*, is one of many photographs of such a pattern, taken with an exposure of about 15 to 30 seconds, and represents the conditions when adjustments are made for maximum energy in the secondary circuit.

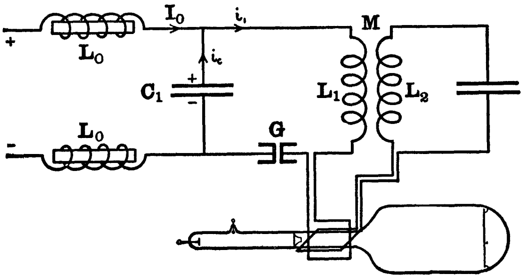

FIGURE 13.

Knowing, as will be adequately proved later, that the secondary oscillation is sinusoidal, the primary current, plotted to time, and its phase relation to the secondary current, can readily be derived from the patterns mentioned above. In *c* of Plate 1 the vertical distance d_1 to the primary loop above, from any point on the horizontal line distant d_2 from the center or undeflected spot, gives the instantaneous primary current, i_1, and the simultaneously secondary current, i_2. A sine curve of amplitude represented by the secondary deflection is drawn, and the time coördinate for any corresponding values of i_1 and i_2 is the time, obtained from the sine curve, at which the current coördinate is i_2. The direction of the spot of light is indicated by the arrows. The curve marked I_1, in Figure 14, shows the development of two figures, both reduced to the same scale for better comparison. I_2 in the figure is the secondary current. Seven such developments were made representing entirely different conditions, but in each case the phase of I_1 with respect to I_2 was practically the same as is shown in Figure 14, and the shapes of the I_1 curves differed so slightly that, to save confusion, they are not reproduced.

Examination of the photograph and of the developments show, as was stated in Part I, that there is no inverse current. Although the primary wave appears to have twice the period of the secondary oscillation, if the slope of the curve, or $-\frac{di_2}{dt}$ which is proportional to the resulting induced electromotive force in the secondary circuit, be plotted, a curve of the same period as I_2 is obtained. This e. m. f. curve is shown at E in Figure 14.

If, now, the ordinates of the e. m. f. curve be multiplied by the corresponding values of the secondary current, a quantity proportional to the instantaneous rate at which energy is being transferred to the secondary is obtained, and if plotted, gives the curve marked W in Figure 14. The portions of the curve below the axis of time are negative, and represent a return of energy to the primary circuit. The algebraic sum of the areas under the four loops is proportional to the total energy permanently delivered to the secondary circuit in one cycle. It is apparent that very little energy is returned to the primary circuit, and that the second half of the primary loop gives the greater amount of energy to the secondary circuit, the first part of the primary discharge being more or less irregular on account of the sudden breaking down of the high initial gap resistance and the superposed higher harmonies resulting from the sudden shock to the system.

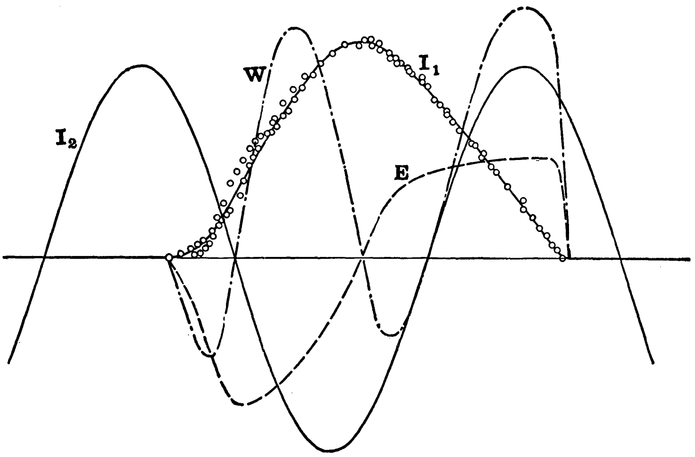

FIGURE 14.

I_1 . . . . . Primary Discharge Wave.
I_2 . . . . . Secondary Wave.
E . . . . . Electromotive Force due to I_1.
W . . . . . Power Delivered to Secondary Circuit.

In Part I it was stated that the primary current loops occur every two or more secondary oscillations. In this case the primary wave, considered as an intermittent function, could be analyzed into harmonics. Instead, however, of analyzing the current wave, the equivalent problem of expanding the resulting e. m. f. wave into harmonics can easily be done if, as is seen by reference to Figure 14 to be roughly true, the e. m. f. curve be assumed to be an intermittently repeated sine cycle.

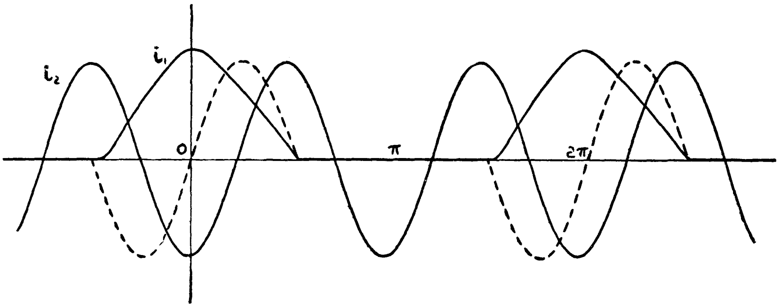

Figure 15.

Suppose the particular case of a discharge every two secondary oscillations (I. C. F. = 2) be considered in detail. Figure 15 indicates the conditions of the problem. The full line sine curve, marked i_2 represents the secondary oscillation which has thus far been considered, or in other words, the primary harmonic of maximum intensity. The other full line, marked i_1, is the primary discharge, and the dotted line the approximate e. m. f. wave which was referred to above.

The function

$$e = E \sin 2x \Big|_0^{\pi/2} \qquad e = o \Big|_{\pi/2}^{\pi}$$

is to be developed into a Fourier series of the form

$$e = a_1 \sin x + a_2 \sin 2x + a_3 \sin 3x + \ldots\ldots$$

where any coëfficient a_m is given by the expression

$$a_m = \frac{2}{\pi} \int_0^{\pi} f(x) \sin mx \, dx = \frac{2}{\pi} \int_0^{\pi/2} E \sin 2x \sin mx \, dx$$

The result is expressed below.

$$e_2 = E\,(.43 \sin x + .50 \sin 2x + .26 \sin 3x - .061 \sin 5x + .028 \sin 7x - .017 \sin 9x + \ldots.)$$

If the harmonics are to be expressed in terms of time and the period of the e. m. f. wave, which is the same as the period of the secondary oscillation, the substitution

$$2x = 2\pi nt \qquad \text{or}$$

$$x = \frac{2\pi nt}{2} \qquad \text{is to be made.}$$

Then $e_2 = E\Big(.43 \sin 2\pi\left[\frac{n}{2}\right]t + .50 \sin 2\pi nt + .26 \sin 2\pi\left[\frac{3n}{2}\right]t - .061$ $\sin 2\pi\left[\frac{5n}{2}\right]t + .028 \sin 2\pi\left[\frac{7n}{2}\right]t - .017 \sin 2\pi\left[\frac{9n}{2}\right]t + \,.\,.\Big)$

The results for I. C. F. equal to 3 and 4 are given below.

I. C. F. = 3

$$e_3 = E\Big(.21 \sin 2\pi\left[\frac{n}{3}\right]t + .33 \sin 2\pi\left[\frac{2n}{3}\right]t + .33 \sin 2\pi\left[\frac{3n}{3}\right]t + .24 \sin 2\pi\left[\frac{4n}{3}\right]t + .10 \sin 2\pi\left[\frac{5n}{3}\right]t - .04 \sin 2\pi\left[\frac{7n}{3}\right]t - \,.\,.\,.\Big)$$

I. C. F. = 4

$$e_4 = E\Big(.12 \sin 2\pi\left[\frac{n}{4}\right]t + .21 \sin 2\pi\left[\frac{2n}{4}\right]t + .26 \sin 2\pi\left[\frac{3n}{4}\right]t + .25 \sin 2\pi nt + .20 \sin 2\pi\left[\frac{5n}{4}\right]t + .13 \sin 2\pi\left[\frac{6n}{4}\right]t + \,.\,.\,.\,.\Big)$$

A classification of the harmonics is given in the adjoining table, where the columns are headed according to the I. C. F.

The coëfficients of the various terms in the developments mean very little, but the existence of most of the harmonics, given in the table, has been verified by wave meter readings.

A much more beautiful proof of the existence of the harmonics is presented by Braun tube oscillographs. If, in addition to the arrangement of circuits shown in Figure 13 for obtaining the primary wave form, another adjustable secondary circuit be used, excited by the primary current, and having a deflecting coil also about the Braun tube and parallel to the primary deflecting coil, the pattern observed on the fluorescent screen is the resultant of the deflections of the first sec-

I. C. F.	1	2	3	4	5	6	7
Primary Harmonics	n	$\frac{n}{2}$	$\frac{n}{3}$	$\frac{n}{4}$	$\frac{n}{5}$	$\frac{n}{6}$	$\frac{n}{7}$
		n	$\frac{2n}{3}$	$\frac{2n}{4}$	$\frac{2n}{5}$	$\frac{2n}{6}$	$\frac{2n}{7}$
		$\frac{3n}{2}$	n	$\frac{3n}{4}$	$\frac{3n}{5}$	$\frac{3n}{6}$	$\frac{3n}{7}$
			$\frac{4n}{3}$	n	$\frac{4n}{5}$	$\frac{4n}{6}$	$\frac{4n}{7}$
		$\frac{5n}{2}$	$\frac{5n}{2}$	$\frac{5n}{4}$	n	$\frac{5n}{6}$	$\frac{5n}{7}$
				$\frac{6n}{4}$	$\frac{6n}{5}$	n	$\frac{6n}{7}$
		$\frac{7n}{2}$	$\frac{7n}{3}$	$\frac{7n}{4}$	$\frac{7n}{5}$	$\frac{7n}{6}$	n
			$\frac{8n}{3}$		$\frac{8n}{5}$	$\frac{8n}{6}$	$\frac{8n}{7}$
		$\frac{9n}{2}$		$\frac{9n}{4}$	$\frac{9n}{5}$	$\frac{9n}{6}$	$\frac{9n}{7}$
			$\frac{10n}{3}$	$\frac{10n}{4}$		$\frac{10n}{6}$	$\frac{10n}{7}$
		etc.	$\frac{11n}{3}$	$\frac{11n}{4}$	$\frac{11n}{5}$	$\frac{11n}{6}$	$\frac{11n}{7}$
			etc.		$\frac{12n}{5}$		
				etc.	etc.	etc.	

ondary current, and, at right angles to it, the sum of the deflections due to the primary and the second secondary currents. If, now, the second secondary capacity be varied, there suddenly appears on the fluorescent screen, as resonance for one of the harmonics of the primary is obtained, a Lissajou's figure corresponding to the ratio of frequencies of the two secondary oscillations. In addition to the simple Lissajou's figure, which is due to the free vibration of the two secondaries, there appears a less intense irregular loop due to the intermittent primary discharges.

Plate **1**, cuts *d* and *e*, and *a* and *b* of Plate **2** are photographs of a few of the patterns obtained by the above described method. The second secondary circuit was a wave meter with its coil parallel to the primary deflecting coil, from which it received its impulses. An examination of the primary loop is often instructive in giving the relation of the primary discharge to the secondary oscillation. It is seen that the regular Lissajou's figure may or may not be complete according to the value of the I. C. F. In *b* of Plate **2** the ratio of frequencies is 3 : 1, and the I. C. F. is 3, so that the primary discharges occur once for every journey of the spot over the pattern, thereby distorting a part of the Lissajou's figure.

Cuts *b–f* of Plate **2** are due simply to the deflections of the two secondary oscillations, the second secondary circuit receiving its impulses from the same primary coil which excited the first secondary circuit. Some of the photographs shown were purposely taken with a slight difference in phase to show the double line. Cut *e* of Plate **1** represents the same ratio of frequencies as that of cut *a* of Plate **2** but with a considerable shift in phase.

A consideration of cuts *d–f* of Plate **2** shows that, although the coupling was close, the secondary currents do not depart from the sinusoidal form even while the primary impulse occurs. A possible rough explanation of this non-departure from the sinusoidal form can be had from a consideration of the shape of the primary wave form shown in Figure 14. The primary impulse I_1 of Figure 14 is seen to be approximately a cosine curve, of the same period as the free secondary oscillation, plus a constant, until the maximum current is attained, when the current decreases in a straight line. But by substitution in the differential equation for an oscillatory circuit, one finds that a cosine wave plus a constant or linear function of the time satisfies the conditions of a sine secondary oscillation. The proof of this proposition is not given here.

The shape of the primary wave form, which has just been considered, is determined principally by the changes in resistance which take place in the gap. If there were no change in resistance, and the influence of the secondary current were negligible, the form of the primary current rush would be given by the familiar equation

$$i_1 = \frac{Q_o}{\sqrt{R_1^2 C_1^2 - 4 L_1 C_1}} (e^{-\alpha t} - e^{-\beta t}),$$

where $$\alpha = \frac{R_1C_1 + \sqrt{R_1{}^2C_1{}^2 - 4L_1C_1}}{2L_1C_1}$$

and $$\beta = \frac{R_1C_1 - \sqrt{R_1{}^2C_1{}^2 - 4L_1C_1}}{2L_1C_1}.$$

Q_o is the initial charge in the primary condenser C_1, and L_1 and R_1 are the inductance and resistance in the primary circuit. The curve, which represents this equation, is, as is well known, a rise and fall of current with respect to time, and is aperiodic or oscillatory according as $R_1{}^2$ is greater or less than $4L_1/C_1$. The critical resistance above which the discharge is non-oscillatory is, for the circuits which were used in this investigation, of the magnitude of 100 ohms. As will be seen later, the average resistance of the gap is so low compared to this quantity that the existence of no inverse current cannot be attributed solely to the aperiodic nature of a discharge through a high resistance. Moreover, if the average resistance were high enough to cause the discharge to be aperiodic, the end of the discharge would be asymtotic to the time axis.

The resistance of the gap very rapidly drops from a very high value at the start to a low value. Since the resistance is a function of the current, and very probably a function of the time of which we have no knowledge, it is impossible to derive any exact mathematical expression for the current curve. A consideration of the physical aspects will, however, reveal to some extent the reasons for the shape shown. If, in the differential equation for the primary circuit,

$$L_1\frac{di_1}{dt} + M\frac{di_2}{dt} + R_1i_1 + \frac{\int_o^t i_1dt}{C_1} = \frac{Q_o}{C_1},$$

the term R_1 is suddenly decreased, it is evident that the term $L_1\frac{di_1}{dt}$ will prevent at first a rapid change in current. This, in part, explains the slow rise of current as shown by the first part of the primary wave form. As the discharge progresses the resistance becomes lower, and the current increases, following more closely one of the exponential discharge curves of low resistance. For reasons previously given, the discharge stops as soon as the current becomes zero.

(3) *The Resistance of the Gap.*

It is interesting, by assuming an approximate expression for the primary wave form, to calculate the change in resistance of the gap necessary to give the observed primary current curve. An examination of the experimental curves of Figure 14 shows that the first part of the primary wave can be approximately represented by the expression

$$i_1 = I_1\ (1 - \cos \omega\ t).$$

where now i_1 represents the instantaneous value, and I_1 the maximum value of the primary current, and ω is $2\ \pi$ times the secondary frequency. Time is reckoned from the beginning of the primary discharge.

The corresponding expression for the secondary wave is found by measurements of Figure 14 to be

$$i_2 = I_2 \sin\ (\omega t + 115^\circ).$$

These expressions can now be substituted in the differential equation for the primary circuit,

$$L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} + R_1 i_1 + R_b i_1 + \frac{\int_o^t i\, dt}{C_1} = \frac{Q_o}{C_1},$$

in which R_b is the resistance of the gap, R_1 is the resistance of the rest of the primary circuit.

Also

$$i_c = i_1 - I_o. \quad \text{(See Figure 13)}$$

whence

$$L_1 I_1\, \omega \sin \omega t - M I_2\, \omega \cos\ (\omega t + 115^\circ) + (R_1 + R_b) I_1\ (1 - \cos \omega t)$$

$$+ \frac{(I_1 - I_o)t}{C_1} - I_1 \frac{\sin \omega t}{\omega C_1} = \frac{Q_o}{C_1}$$

Solving for R_b there results

$$R_b = \frac{\frac{Q_o}{C_1} - \frac{(I_1 - I_o)t}{C_1} - I_1\left(L_1\omega - \frac{1}{C_1\omega}\right)\sin \omega t + M I_2\omega \cos\ (\omega t + 115^\circ)}{I_1(1 - \cos \omega t)} - R_1$$

$$= \frac{\frac{Q_o}{C_1} - \frac{I_1 - I_o}{C_1} t - I_1\left(L_1\omega - \frac{1}{C_1\omega} + .91\, M\omega\, \frac{I_2}{I_1}\right) \sin \omega t - .42\, M I_2 \cos \omega t}{i_1}$$

if R_1 be neglected.

If appropriate values for the constants of this expression be taken, and R_b plotted to the current i_1, the curve shown by the dotted line of Figure 16 is obtained.

The change of resistance of the gap can be obtained experimentally by use of a Braun tube provided with electrostatic deflecting plates. These electrostatic plates are connected directly across the gap as shown by Figure 17, causing a deflection perpendicular to that caused by the total current through the gap. In this way a trace of the voltage-current characteristic curve is obtained from which can be derived the resistance corresponding to any current.

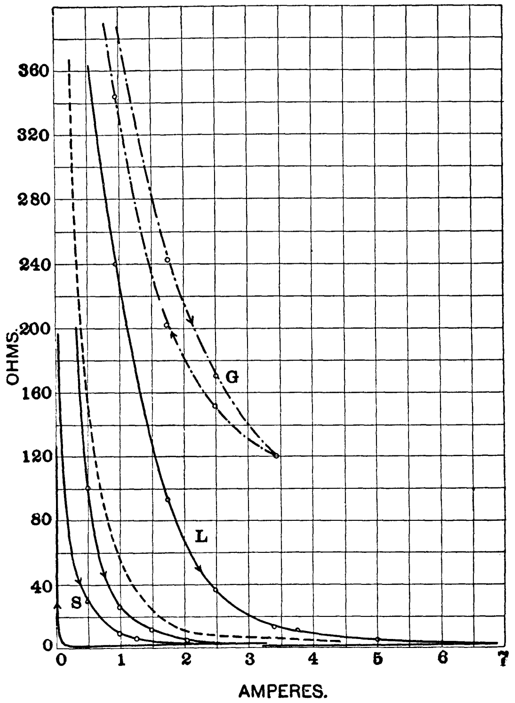

FIGURE 16. Resistance Curves of *Cu-Al* Gap.

G . . . . Glow Discharge.
L . . . . Discharge with Very Long Gap.
S . . . . Discharge with Very Short Gap.
Dotted curve . . . . Calculated.

Cuts *a–e* of Plate **3** are photographs of *E–I* characteristic curves as above described. Cut *a* represents the conditions for a very long gap. The path of the spot of light, in tracing this figure, may be understood from the following. As the condenser charges there is no current through the gap, and hence no current deflection, but the potential of the condenser increases to a certain value determined by the breaking-down potential of the gap. This charging is represented in the photograph by a movement of the luminous spot from A, its undeflected position, to B, the potential at which the gap breaks down, which in magnitude, in this case, is equal to about 450 volts. The instant that the gap breaks down the potential drops, and the current through the gap increases giving the curve, from B to C, roughly resembling a hyperbola. As the current decreases, represented by the line CA in the photograph, the potential remains practically zero, showing that after the gap has been once ionized the resistance remains low until the current becomes zero. The current does not increase in the negative direction for reasons previously given. During the passage of the primary current the capacity, C_1, has been completely discharged and charged in the reverse direction so that, as soon as the current stops, the full potential of the reversed condenser is brought to bear across the gap. This is represented by the point D. Current is now, however, flowing into C_1 at a constant rate, causing the fluorescent spot to move along the voltage axis from D to B to begin a new cycle.

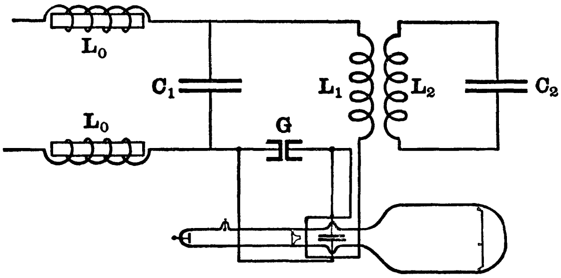

FIGURE 17.

The same kind of diagram is shown in cuts b and c of Plate 3 for shorter gaps. It is evident, as would be expected, that as the gap is shortened, the E–I curve closes in toward the two axes.

It is also seen that with a very short gap the current increase is oscillatory. These oscillations are very rapid, having a wave length of the magnitude of four or five meters, and on account of the extremely high frequency cause the large potential oscillations shown by the blurred space in cut d of Plate 3.

The reason for these superposed higher frequency oscillations is easy to understand if we consider again the rapid drop in resistance represented by the very steep resistance curve for a short gap. A decrease in resistance means an increased current, but the increase in current further causes a decrease in resistance. This action promotes an unstable condition, and would cause a tremendously sudden rush of current if the inductance of the whole circuit did not exert a controlling action. The effect is, however, that the terminals of the gap and the wires in the immediate vicinity of the gap are suddenly robbed of electricity, and because of the inductance of these terminal lead wires, the terminals are charged in the opposite direction. When the potential of the reversed terminals attains a sufficient value this momentary current rush stops and reverses. It is evident, without further consideration, that the conditions are right for the observed superposed oscillations, these oscillations being more intense at the gap and extending back with diminishing amplitude into the primary circuit. This effect will be very apparent in some of the pictures yet to be considered.

Cut *e* of Plate **3** is a photograph taken when, on account of the dryness of the hydrogen, practically nothing but a glow discharge could be obtained. The gap in this particular case was traversed by a high frequency current. The photograph is introduced only for the small curved point at the right hand end of the potential deflection, which is the characteristic of the glow discharge.

Cut *f* of Plate **3** was taken in the same manner as the pictures just described except for the addition of a secondary deflection coil parallel to the primary coil about the tube. In this way there is obtained a spreading out of the diagram, and a clearer view of the actual path of the luminescent spot. The helical path from right to left results from the secondary current oscillation, and superposed primary potential oscillations due to the influence of the secondary vibrations on the primary circuit, both occurring during the charging of the primary condenser. The abrupt end represents the point at which the gap breaks down and the spot moves very rapidly, at first, over the primary discharge loop.

The change in resistance with changing current, derived from these E–I characteristics, gives curves of the general shape shown by the full line curves of Figure 16. The curve marked L was derived from cut *a* of Plate **3**, and represents the change in resistance of a very long gap. The other two full-line curves are for shorter gaps, and, in the extreme corner, is suggested the condition for decreasing current which completes the cyclic resistance changes.

It is seen, on examination of Figure 16, that the dotted curve, derived from an assumed expression for the primary wave form, agrees well in shape with the experimental curves (heavy lines). The scales of the curves serve only to give an approximate idea of the magnitudes of the resistances at different currents, for the position of the curves depends upon the arc length and undoubtedly upon the period of discharge. It is worthy of note that the resistance at zero current is very high, thus admitting of a high initial charge in the primary condenser before the gap breaks down. The resistance curves are very steep, being much steeper than the corresponding curves for the Poulsen arc. It is, in part, this steepness which adapts the gap to the production of very high frequency oscillations. The very rapid reëstablishment of the high resistance is also of primary importance in the action of the gap with high frequencies.

The upper dot-and-dash curve is for the curved point at the end of the potential deflection in cut *e* of Plate **3** just mentioned, and represents the conditions for glow discharge.

(4) *The Inverse Charge Frequency* (*I. C. F.*).

Reference has often been made to the I. C. F., the value of which, as was stated, depends upon the wave length of the secondary oscillation, the size of the primary condenser C_1, and the value of the supply current I_0. In order to show that the I. C. F. has, under most conditions, a perfectly definite value, and at the same time, to illustrate some other points concerning the system, the photographs of Plate **4** were taken.

The arrangement of circuits, for the figures under discussion, was as follows: Two parallel deflecting coils were placed about the Braun tube, and so situated as to deviate the cathode beam in a direction perpendicular to the electrostatic deflection. One of these coils was connected in the primary circuit and the other in the secondary circuit. The electrostatic deflecting plates were connected to the terminals of the primary condenser C_1.

The oscillograms of Plate **4** represent, therefore, the sum of the primary and secondary currents by deflections in the vertical direction, and the potential of C_1, by deflections in the horizontal direction. In all of the cuts the straight lower portion results from the secondary oscillation during the charging of C_1, when the gap current is zero.

The explanation of cut *b* will serve for all of the pictures of Plate **4**. At point *A* the condenser C_1 is charged to a potential sufficient to jump across the gap. When the primary discharge begins, the spot of light moves very rapidly at first over the loop *ABC*. This discharge starts or maintains the secondary oscillation, so that the vertical deflection is due to the primary current plus the simultaneous secondary current. During the discharge the potential of the primary condenser falls and increases in the opposite direction, so that, at the end of the discharge, represented at *C*, the condenser potential is reversed. At point *C* the primary discharge is completed. The rest of the diagram from *C* to *A* is due to the secondary oscillation, which causes the vertical deflection, and the uniformly changing potential of the primary condenser while charging, which causes the horizontal deflection from *C* to *A*.

The number of secondary oscillations taking place during one primary cycle, and which has been called the I. C. F., is clearly shown by the photographs. In the case of cut *b*, the secondary completes one period during the primary discharge, and three complete secondary periods during charging from *C* to *A*, so that the I. C. F. is 4.

The instant at which the primary discharge begins and ends with reference to the secondary wave, is shown to be the same as was derived in the section on the primary wave. The high harmonic oscillations in the primary which occur, as has been mentioned, after the high resistance of the gap is broken down, are apparent in the beaded appearance of the upper loops of the oscillograms.

In cuts *a–e* of Plate **4** the spot travelled over the patterns in an anticlockwise direction. The I. C. F.'s are respectively 3, 4, and 6. In cuts *a* and *b* the undeflected position of the spot is shown, and the relative magnitudes of the direct and inverse potentials of the primary condenser can be noted.

The beats, shown in cuts *c–f* of Plate **4**, are due to the interference of two oscillations in a doubly-periodic secondary system employed in this case. The second-secondary oscillation is due to the vibration of an helix, a few turns of which were included in the secondary circuit. The luminous spot in cut *d* travelled in a clockwise direction.

(5) *Resistance Damping.*

In order to obtain an oscillogram of a variable which is a function of time, it is necessary to use some device which will give a uniform time axis to the figure. For instance, if it is desired to obtain an oscillograph of the commercial alternating current, one passes the current through the deflecting coil about the Braun tube. There appears on the screen a straight line, which results from the to-and-fro movements of the luminous spot over the same straight path. In order to see the current wave developed with respect to time, it is necessary to observe the line deflection in a revolving mirror, its axis being parallel to the line deflection. If a photograph is to be taken, it is further necessary to drive the mirror by some synchronous device so that the image of the developed figure may be stationary on the photographic plate for a time sufficient to make the exposure. This synchronizing device is not difficult to arrange when using commercial alternating currents, but when it is desired to take an oscillogram of a high frequency current or condenser discharge, it is usually impossible to make the necessary synchronization. When using high frequency currents, the velocity of the spot of light on the fluorescent screen is so great that, in order to obtain a photograph, it is necessary that the cycle of changes, as shown by the pattern on the screen, be repeated many hundred thousand times with such regularity and certainty that the image is always in exactly the same position. The requirements of both the acting system and the synchronizing device are very exacting.

The development of the time axis can be most effectually accomplished with the system under discussion by the very simple connection which was used in the last section. The electrostatic plates, which cause a deflection perpendicular to the current coils, are connected to the terminals of the primary condenser C_1. During the interval between primary discharges, when the primary condenser is charging, the primary current is zero, and the main or charging current is almost perfectly constant on account of the large inductances in the mains. This uniform charging causes a uniform increase in potential of the condenser C_1, and hence a uniformly developed time axis on the fluorescent screen. The oscillations of the secondary, or any effect started by the primary discharge, is thereby developed, as is shown by the lower portions of the cuts of Plate 4.

This arrangement for the development of current or potential deflection with respect to time is of the greatest use in many ways. Its application will be illustrated here by showing the damping curves with oscillations of a frequency of two million or more per second.

Cuts *a* and *b* of Plate 5 represent the damping of the secondary oscillations due to the addition of resistance in the secondary circuit. The primary capacity and supply current were so adjusted as to give large values of the I. C. F. in order that as many secondary oscillations as possible might appear in the damped oscillation trains shown. The adjustments for the pictures of Plate 5 were so made that each oscillation train is just completed before the beginning of the next. The trains, therefore, succeed each other with no intervals of rest. By adjustments of the supply current or primary capacity it is possible to lengthen or shorten the interval between the primary discharges, and by varying the resistance in the secondary circuit the number of oscillations in one train or the damping can be varied at will. The damping is evidently exponential in fulfilment of the familiar theory.

Cuts *c–f* of Plate **5** and cut *a* of Plate **6** are the results of adding to the arrangement of circuits just considered, a second secondary circuit, excited by the primary discharge and with its deflecting coil placed parallel to that of the first secondary. There results, therefore, a doubly-periodic secondary system having two secondary circuits inductively coupled together. The doubly-periodic secondary oscillation gives the beats and curious figures shown. Cuts *c* and *d* are due to the addition of two oscillations differing widely in frequency. As will be seen from the description of the figures, the second oscillation is in one case over twice and in the other case almost three times the frequency of the main secondary oscillation.

Cut *a* of Plate **6** shows beats taken with almost undamped oscillations. The wave lengths are not recorded but they were probably of the magnitude of 100 meters.

(6) *Damping in a Circuit Containing a Spark Gap.*

When the dissipation of energy in an oscillatory circuit is proportional to the square of the current, as is the case in a constant resistance, the damping is exponential. If, however, the resistance is a function of the current the energy dissipation is no longer proportional to the square of the current, and the damping no longer exponential. For instance, the resistance of a spark gap or arc is a function of the current, the resistance being greater the smaller the current through the gap.

Richarz and Ziegler[9] in 1900 observed, in a revolving mirror, the straight line deflection which is produced in a Braun tube when a condenser is rapidly discharged across a spark gap and through the deflecting coil. The frequency of the oscillations was very low. On account of the impossibility of taking a photograph, we have only their description of the phenomenon as seen in the revolving mirror. In appearance the figure resembled the backbone of a fish, or, in other words, a long straight line, due to the undeflected spot, and at intervals along the line pairs of equally inclined short straight lines, as one would indicate an arrow point. The short lines were due to the more intense maximum deflections during a train of oscillations, the separate oscillations being entirely undiscernible. The results showed that the damping due to a spark gap is not exponential but approximately linear.

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[9] F. Richarz u. W. Ziegler, Ann. d. Phys., **1**, 468, 1900.

Zenneck,[10] in 1904, obtained further experimental proof of the approximately linear damping due to a spark gap. He photographed the line deflection, and by a process of projection from the several brighter spots, due to the decreasing amplitudes of the oscillations, derived the damping curves. Frequencies up to 1800 per second were used by him.

Heydweiller,[11] in 1906, showed that the results obtained by the above mentioned experimenters can be deducted theoretically. Heydweiller assumes, in deducing the linear damping, that the gap has a characteristic expressible in the form.

$$e = a + \frac{b}{i}.$$

where e and i are the voltage across and current through the gap, respectively, and a and b are constants. He further assumes that b is negligible, which reduces the conditions to the assumption of a constant voltage across the gap. Solving the differential equation for the discharge of a condenser across a constant potential gap, he obtained rectilinear damping.

If a discharge gap be substituted for the secondary resistance in the arrangement of circuits which was used in the last section for obtaining plain resistance damping, very clear oscillograms can be obtained of the oscillation trains when the damping is caused by a gap. Although the inherent irregularity of some metallic gaps, when used in the secondary circuit, causes some irregularity of the oscillographs, yet good photographic records can be obtained, as is shown by the cuts of Plates **6** and **7**. In order to obtain a potential sufficient to maintain the discharge across the secondary gap, it was necessary to use a large primary condenser and supply current, and to make the ratio, $\frac{N_2}{N_1}$, of the secondary to primary turns on the helix large.

Cuts *b* and *c* of Plate **6** show two of the pictures first taken, and illustrate well the linear damping. The gap length was very short; the terminals were of aluminum.

Further investigation showed that the oscillation train took on entirely different aspects according as the discharge could be classed as a *pure arc*, or a *spark discharge*. When the discharge is a pure arc, the separate oscillations are regular and practically sinusoidal, and the damping is still linear. If the discharge is classed as a spark discharge, although the damping is linear, the separate oscillation loops are distorted as will appear presently.

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[10] J. Zenneck, Ann. d. Phys., **13**, 822, 1904.

[11] R. Heydweiller, Ann. d. Physik., **19**, 646, 1906.

Cut *d* of Plate 6 represents the condition when the discharge terminals of the secondary gap are carbon. The discharge was quiet and very brilliant, resembling, as indeed it was, the pure carbon arc operating, however, at a frequency of 5.7 × 10^5 oscillations per second.

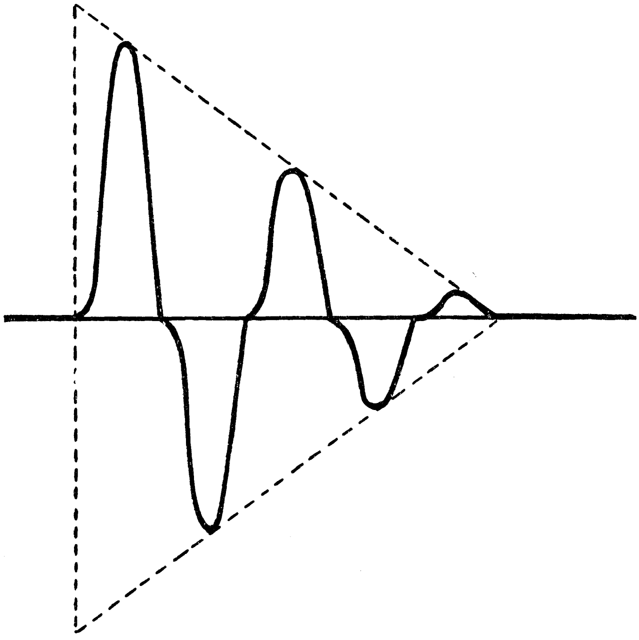

FIGURE 18. Form of Spark Gap Damping Curve.

Cut *e* of Plate 6 gives the appearance of the oscillogram when the terminals are of aluminum in air. The discharge in this case, as well as for cuts *b* and *c*, was probably a pure arc due to the carbon and other impurities in the aluminum. In appearance, the discharge was brilliant and similar to the carbon arc.

Magnesium terminals usually give the pure-arc discharge-form of damping curve, due probably to the large amount of magnesium vapor present in the discharge, or possibly to the burning of the magnesium into the oxide.

Cut *f* of Plate 6 and the pictures of Plate 7 represent the appearance of the *spark discharge* oscillograms. When the temperature of the discharge is kept low the conductivity of the gap is not maintained over the interval of zero current by the presence of incandescent metallic or carbon vapor, and the high resistance of the gap is partially established at each crossing of the axis by the current curve. This necessitates a reionization of the gas at the beginning of each current loop, or the breaking down of a possible oxide film, thereby distorting the wave in the neighborhood of the axis, as is shown by the figures.

The general form of the curve for spark damping, which is indicated in the photographs, was at times momentarily clearly outlined on the fluorescent screen and is shown by the drawing of Figure 18. Apparently, in some of the photographs, the loops begin, in point of time, before the ending of the previous loop. This apparent paradox is due to the slight shift in the time axis resulting from the reaction of the strong secondary discharges upon the potential of the primary condenser.

The oscillogram photographs of spark damping here shown were taken for aluminum terminals because of the greater regularity of the discharge between terminals of that metal. Many other metals were tried, such as copper, cadmium, zinc, etc., and in practically every case in which the discharge was a spark-discharge, the oscillations took the same form as is shown in Figure 18.

When one of the terminals is carbon or magnesium, the current loops on one side of the time axis are of the pure arc form, while those on the other side are of the spark-discharge form.

If the terminals are dissimilar there is usually evidence of a rectifying effect. Particularly is this so if one terminal is of aluminum and the other of copper or iron. Cut *d* of Plate **7** shows this rectification.

The effect of hydrogen on the discharge is indicated by cuts *e* and *f* of Plate **7**, which were taken under the same conditions except for the H surrounding the gap terminals in the case of cut *f*. The hydrogen serves, in this case, principally to ensure a spark rather than an arc discharge, and probably increases the damping.

The outward appearance of the discharge is in no way an indication as to whether the oscillogram takes the arc or spark form. The form of the oscillogram serves conveniently to differentiate between the pure arc and the spark discharges, when the terms arc and spark are applied to discharges operating on alternating currents. The discharge of the *Cu-Al* oscillation gap, which has been studied in this investigation, cannot, according to this definition, be called an arc, but is a spark discharge.

The photographs here shown of gap damping furnish in no way a complete discussion of the subject, but are presented to give additional proof of the existence of linear damping in a circuit containing a spark gap, and to show that there are two distinct forms of the oscillation trains according to the nature of the gap.

(7) *Notes Concerning the Mechanism of Conduction in the Cu-Al Gap.*

Very little can at present be given concerning the exact nature of the conduction which takes place in the gap under discussion and the office of the necessary hydrogen. No oscillations can be obtained unless the gap is immersed in some gas rich in hydrogen, but the latter alone gives by far the best results. In any case the gas must be moist. As was shown early in Part I, the absence of metallic vapor indicates that the conduction is probably affected entirely by the ionization of the surrounding gas. Since, as was also observed, the metal used for the anode makes little difference in the operation of the gap, and since aluminum is the only metal which works at all well as cathode, it is safe to say that it is the aluminum cathode, working in conjunction with the hydrogen, which gives the characteristic properties of the oscillation gap which has been partially studied in the foregoing pages. It might be mentioned here that magnesium acts to some extent as cathode, but, on account of its low vaporizing point, works very irregularly and unsatisfactorily. The discharge, in this case, is intensely green showing vaporization.

The fact that moisture in the hydrogen is necessary indicates that an oxidation of the aluminum plays some part in the operation. The necessity of an hydrogen atmosphere leads one to believe that perhaps a reduction of the ever present aluminum oxide film at some time during the cycle may take place, there possibly being a cyclic change of oxidation and reduction of the aluminum determined by the temperature at various instants during one primary discharge. For instance, it may be that some action such as follows takes place. At the beginning of the discharge, the thin oxide film makes necessary a high breaking-down potential in order to start a discharge. As soon, however, as the discharge is started, H ions are conveyed to the aluminum cathode, and, since the atmosphere about the terminal is H, reduce the oxide film. The free surface of the aluminum is thereby exposed, and the resistance drops to a low value. This reduction would be the greater the larger the current, and there would result the very rapid drop in resistance which is shown in the curves of Figure 16. As soon as the discharge stops the aluminum partially reoxidizes, thereby reëstablishing the initial high resistance.

It is probable that the regularity of the gap is partly due to the fact that the discharge takes place for some time at one definite point on the aluminum, this confinement of the discharge to one place resulting possibly from the protecting oxide film over the rest of the surface.

Part III.

Practical Considerations and Applications.

(1) *Practical Considerations.*

From a practical point of view interest centers on the question of the amount of power obtainable from the system. The gap is not a high-power generator of electrical oscillations; its advantages lie in simplicity and regularity. The conditions for maximum power were considered in Part I, and it was seen that the maximum power efficiently obtained from one gap at 100 meters wave length is about 40 to 45 watts. It is probable, although no extensive tests have yet been made, that the power obtainable is greater at longer wave lengths.

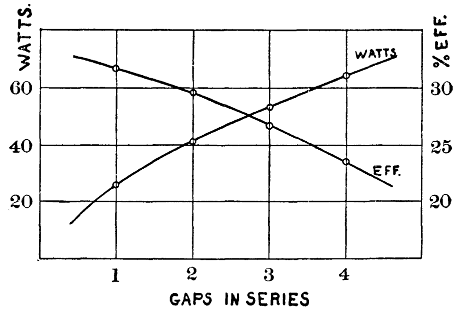

Figure 19. Gaps in Series.

If greater power is required, gaps can profitably be operated in series. Two gaps work perfectly and three gaps well on 500 volts, with much increased power output. Four gaps were satisfactorily run on 1000 volts, but in general there is a slight sacrifice of regularity of operation as the number of gaps in series is increased.

The amount of power obtained, when gaps are operated in series with a definite supply current, is not directly proportional to the number of gaps. When two gaps are operated in series, the power output is almost twice that from one gap. When more gaps are connected in series, the gain in power is much less, the greater the number of gaps the less the gain in power output.

The average voltage across one gap ranges from 90 to 150, but is, under most conditions, about 100. As the number of gaps in series is increased, the current being constant, the voltage across the series is practically proportional to the number of gaps.

The efficiency of the system, when gaps are operated in series, decreases as the number of gaps is increased.

The following table and the curves of Figure 19 give an idea of the result of increasing the number of gaps in series. The values of the efficiency and power may be somewhat misleading as the adjustments were not for conditions of maximum power and efficiency. The general shape of the curves, however, may prove of interest:

No. of Gaps.	I_0.	E.	R.	I. R.	Eff.
1	.55	145	15.9	25.5	32.5 %
2	.55	260	15.9	39.3	27.5
3	.55	360	15.9	55.0	27.0
4	.55	500	15.9	64.8	23.6

As was stated in Part I, a proper choice of dynamo permits the omission of the external resistance. The dynamo, for use in this manner must be characterized by a rapidly falling voltage-current curve in order that the voltage will increase if the discharge tends to stop. The high voltage on open circuit of a generator of this kind also serves automatically to start the gap or gaps.

(2) *Applications.*

Various applications of the continuous oscillations might well be spoken of, but reference will be made to only three, i. e.: the use of the oscillation system in conjunction with a Braun tube for demonstration; the calibration of a wave meter by means of harmonics; and wireless telegraphy and telephony.

The simplicity and convenience of the system as a generator of continuous high frequency oscillations render the apparatus particularly suitable for demonstration and laboratory use. Especially is the system of value when used in connection with a Braun tube, for, with such an equipment, many of the phenomena of electrical oscillations can be visualized, such as the damping due to resistance, the damping due to radiation in an antenna, etc.

As was pointed out in Part II, two secondary circuits of different periods can be caused to oscillate, the exact ratio of frequencies being given directly by the resulting Lissajou's figure. If, then, the period of one of the secondary circuits is fixed and accurately determined in some manner, the period of the second variable secondary circuit is given in terms of the first or standard. In this way, with proper adjustments, a large number of determined periods can be obtained, and an accurate calibration of a wave meter made.[12]

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[12] Suggested by Professor G. W. Pierce.

The system can, of course, be readily used for wireless telegraphy provided some method such as a chopper be used for making audible the continuous transmission of power. One gap operating on from .5 to .8 ampere will undoubtedly transmit up to 70 miles with some advantages over the other systems. In addition to the advantages of high efficiency, one wave length, etc., is the great gain in simplicity and regularity, and the advantage of working directly on the commercial voltages for hours with no attention.

One of the most interesting applications of the aluminum-copper gap is its successful use in wireless telephony. Professor G. W. Pierce and the author have given the apparatus a thorough test in connection with wireless telephony, and have carried on conversations for several hours at a time between two distant stations with practically perfect articulation. The remarkable constancy and regularity of the system as a generator of continuous oscillations has been proved to be of great value for the wireless transmission of articulate speech. This will probably be the subject of a later communication.

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PLATE 1.

MOUNTING OF BRAUN TUBE.

a.

b.

Spectrum of Gap
with
Aluminum Comparison.
Spectrum.

c.

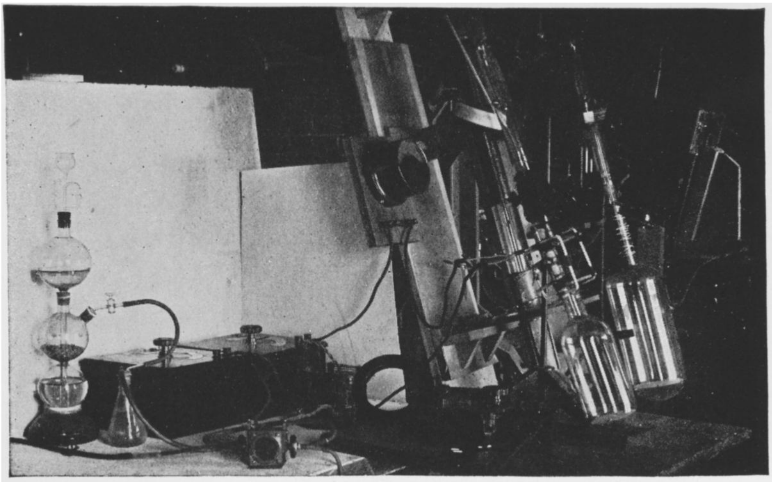
I_0 = .73 ampere.
λ_2 = 110 meters.
I. C. F. = 5.

d.

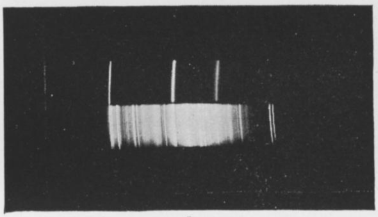
λ_2 = 118 meters.
λ_3 = 236 meters.
Ratio = 1:2.
I. C. F. = 4.

e.

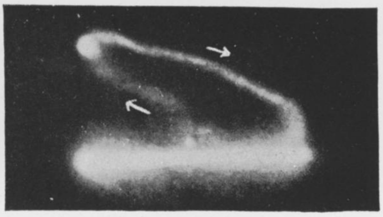
λ_2 = 76 meters.
λ_3 = 114 meters.
Ratio = 2:3.
I. C. F. = 4.



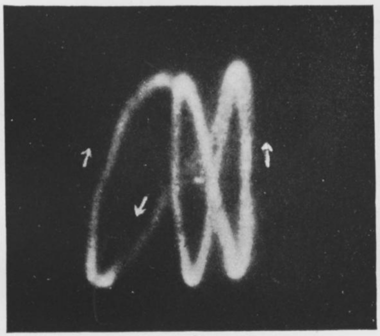
a



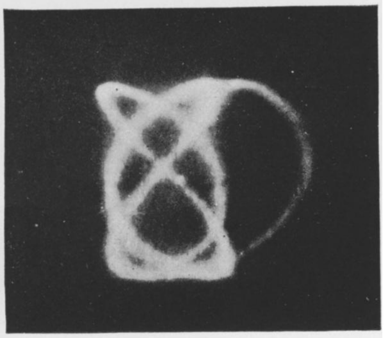
b



c



d



e

PLATE 2.

LISSAJOU'S FIGURES.

a.

λ_2 = 80 meters.
λ_3 = 120 meters.
Ratio 2:3.
I. C. F. = 6.
I_0 = .65 ampere.

b.

λ_2 = 158 meters.
λ_3 = 474 meters.
Ratio 1:3.
I. C. F. = 3.
I_0 = 1 ampere.

c.

λ_2 = 173 meters.
λ_3 = 231 meters.
Ratio = 3:4.

d.

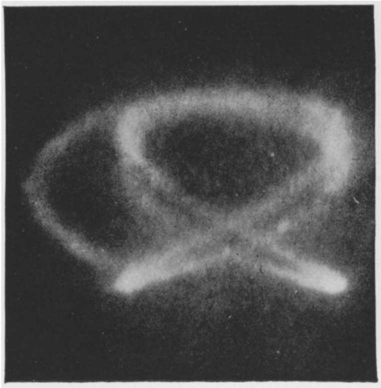
λ_2 = 180 meters.
λ_3 = 300 meters.
Ratio = 3:5.

e.

λ_2 = 200 meters.
λ_3 = 250 meters.
Ratio = 4:5.

f.

λ_2 = 180 meters.
λ_3 = 315 meters.
Ratio = 4:7.



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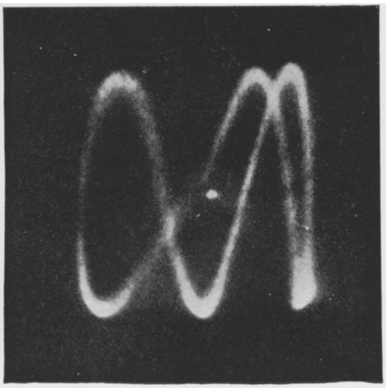

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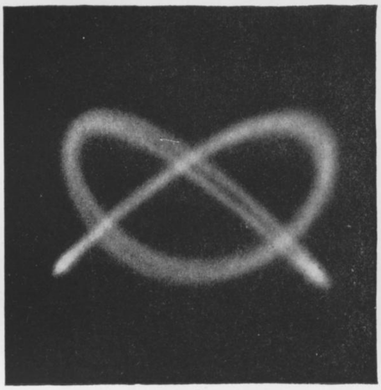

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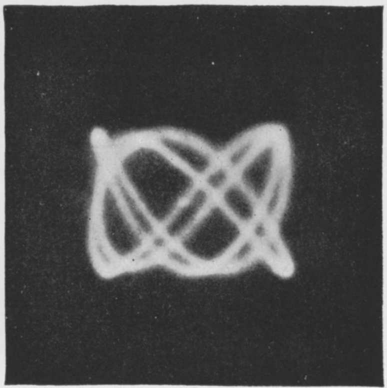

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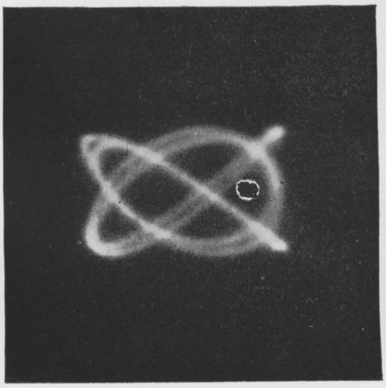

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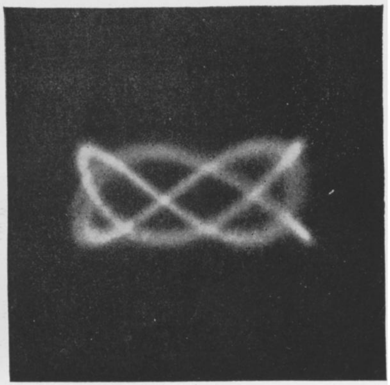


f

PLATE 3.

$E-I$ CHARACTERISTICS.

a. — *Very Long Gap.*

I_0 = .55 ampere.
1 cm. = 4.5 amperes (vertical).
2 cm. = 250 volts (horizontal).

b. — *Long Gap.*

I_0 = 1.0 ampere.
1 cm. = 4.25 amperes (vertical).
1 cm. = 250 volts (horizontal).

c. — *Short Gap.*

I_0 = .54 ampere.
1 cm. = 1.3 amperes (vertical).
1 cm. 230 volts (horizontal).

d. — *Very Short Gap.*

I_0 = 1.5 amperes.
1 cm. = 4.25 amperes (vertical).
1 cm. = 250 volts (horizontal).

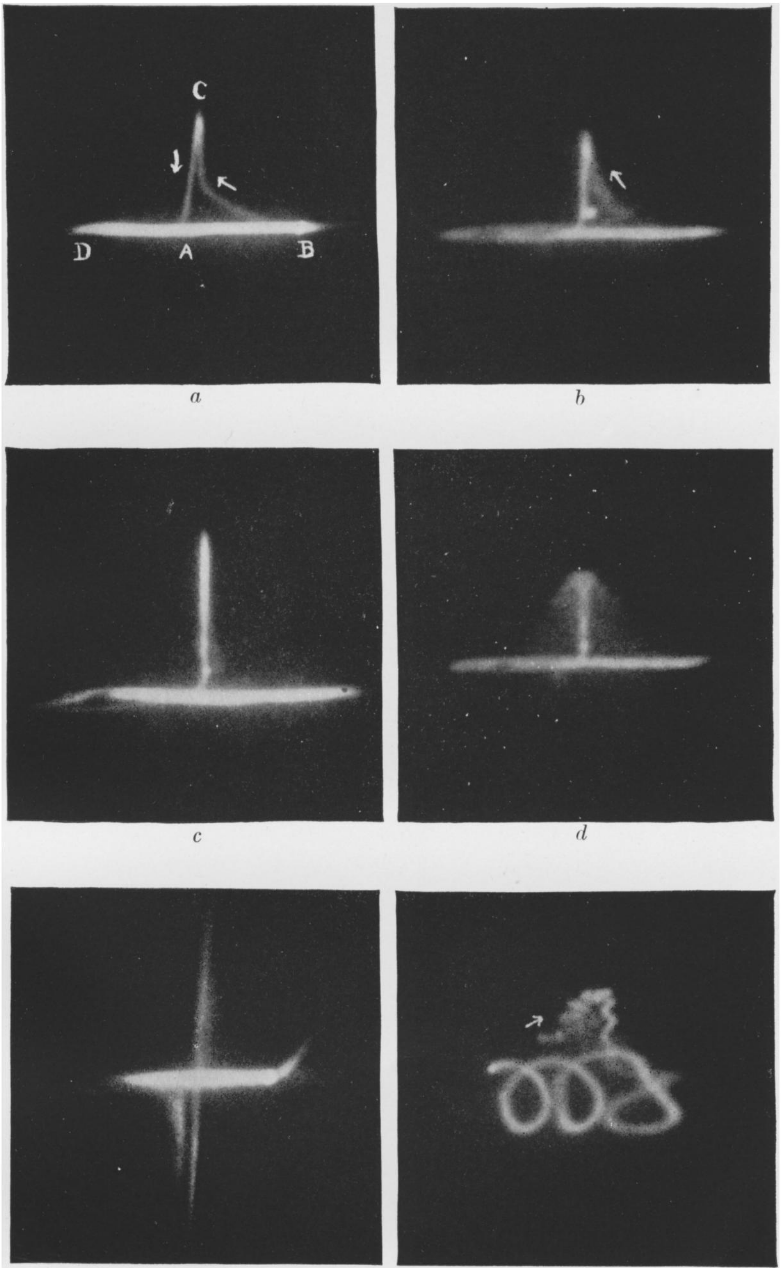
e.

Cu-Al gap operating on oscillatory current. Characteristic of Glow Discharge shown at the end of the potential deflection.

f.

λ_2 = 268 meters.
I_0 = .5 ampere.

CHAFFEE.—IMPACT EXCITATION OF ELECTRIC OSCILLATIONS. PLATE 3.



a *b*

c *d*

e *f*

PLATE 4.

a.

λ_2 = 185 meters.
I_o = .85 ampere.
$C_1 = 178 \times 10^{-5}$ $\mu.f.$
I. C. F. = 3.

b.

I_o = .68 ampere.
$C_1 = 110 \times 10^{-5}$ $\mu.f.$
I. C. F. = 4.

c.

λ_2 = 180 meters.
I_o = .32 ampere.
I. C. F. = 6.

d.

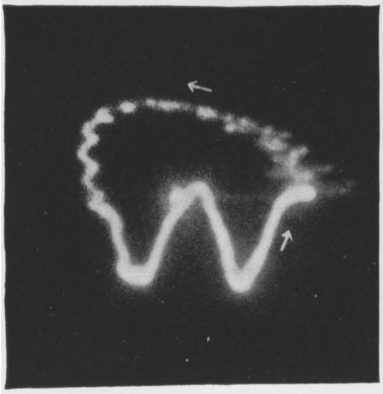
λ_2 = 78 meters.
I_o = .63 ampere.
I. C. F. = 9.

e.

λ_2 = 88 meters.
I_o = .4 ampere.
$C_1 = 170 \times 10^{-5}$ $\mu.f.$
I. C. F. = 11.

f.

λ_2 = 65 meters.
I_o = .5 ampere.
I. C. F. = 7.



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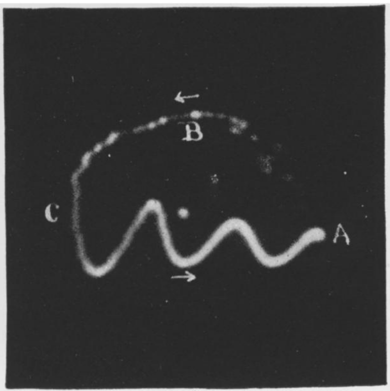

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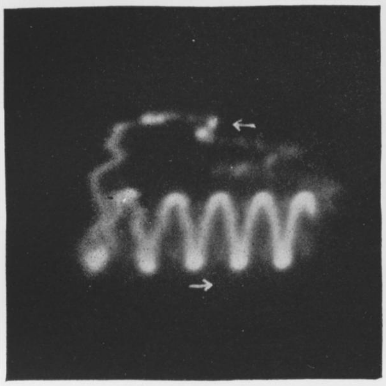

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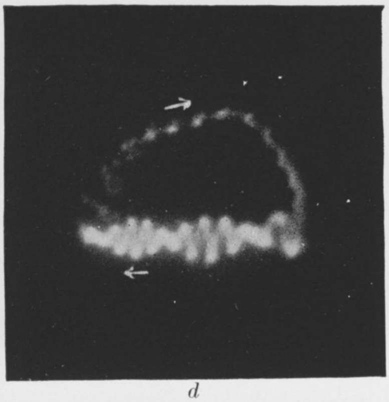

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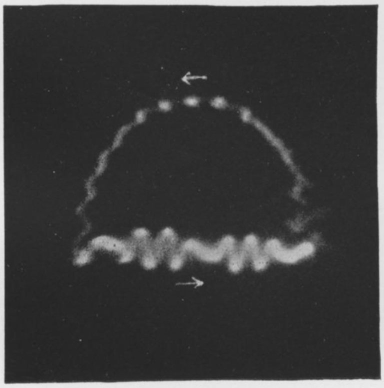

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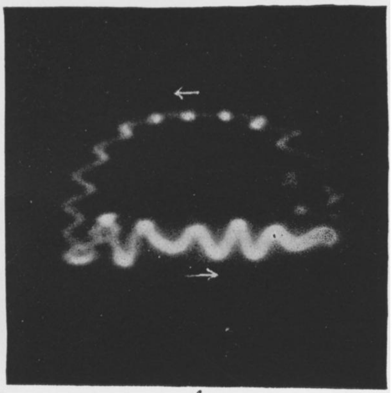


f

PLATE 5.

Resistance Damping and Beats.

a.

$R_2 = 5.9$ ohms.
$\lambda_2 = 112$ meters.
$I_0 = .35$ ampere.
$C_1 = 150 \times 10^{-5}\ \mu.f.$
I. C. F. = 12.

b.

$\lambda_2 = 400$ meters.

c.

$\lambda' = 154$ meters.
$\lambda = 325$ meters.

d.

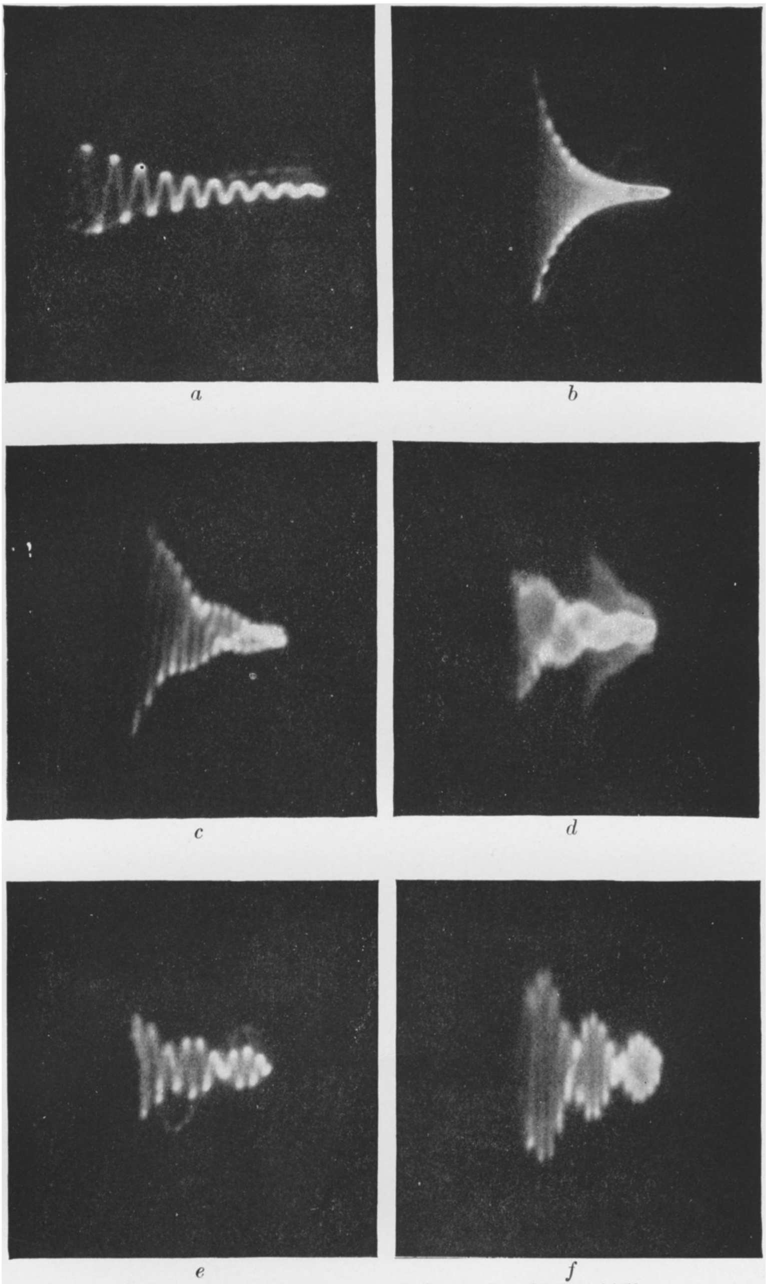
$I_0 = .4$ ampere.
$\lambda' = 140$ meters.
$\lambda = 390.$
$R_2 = 6$ ohms.

e.

$\lambda = 370$ meters.
$\lambda' = 290$ meters.

f.

$\lambda = 215$ meters.
$\lambda' = 255$ meters.



a *b* *c* *d* *e* *f*

PLATE 6.

Gap Damping Oscillographs.

a.
Beats.

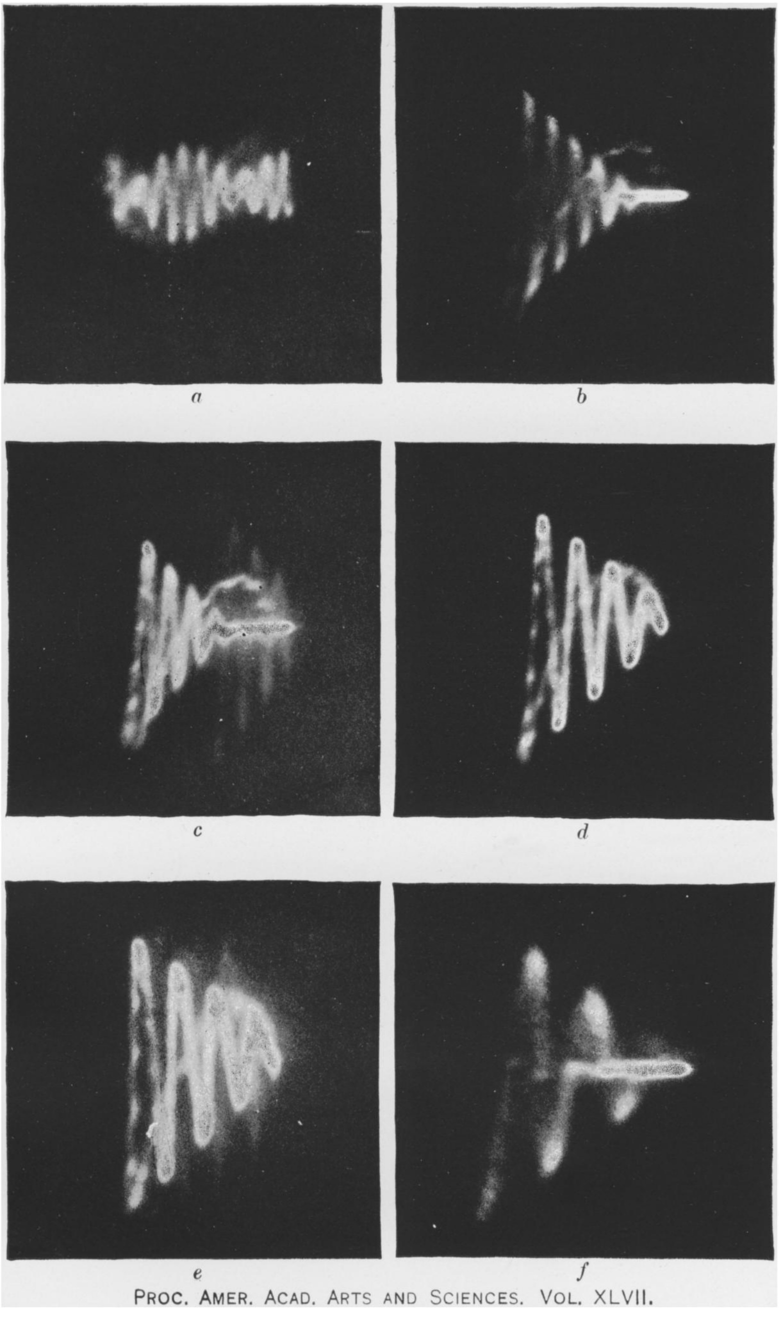
b. — Al-Al in H.
λ = 520 meters.
I_0 = 1.2 amperes.

c. — Al-Al in Air.
λ = 525 meters.
I_0 = 1.2 amperes.

d. — Carbon-Carbon in Air.
λ = 525 meters.
I_0 = 1.4 amperes.

e. — Al-Al in Air.
λ = 575 meters.
I_0 = 1.5 amperes.
Water cooled.

f. — Al-Al in H.
λ = 575 meters.
I_0 = 1.9 amperes.
Water cooled.



a b c d e f

PLATE 7.

GAP DAMPING.

a. — *Al-Al in Air.*
λ = 525.
Water cooled.

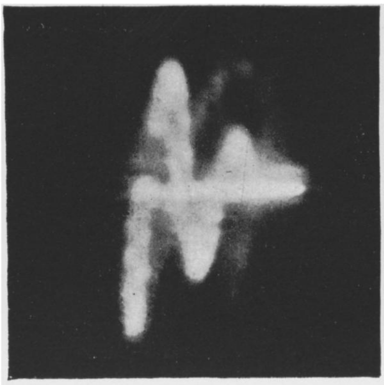
b. — *Al-Al in Air.*
λ = 525 meters.
Water cooled.

c. — *Al-Al in H.*
λ = 525 meters.
Water cooled.

d. — *Cu-Al in H.*
Shows rectification.

e. — *Al-Al Arc in Air.*
λ = 525 meters.
I_0 = 1.3 amperes.

f.
Same as Figure 5, except hydrogen instead of air surrounded gap.



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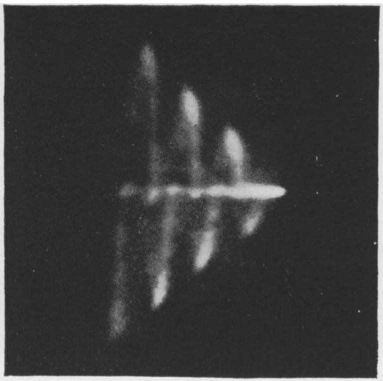

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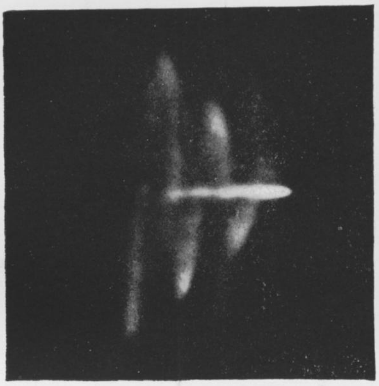

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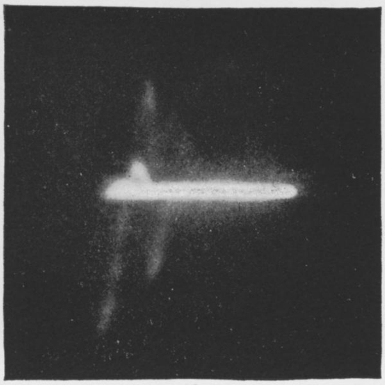

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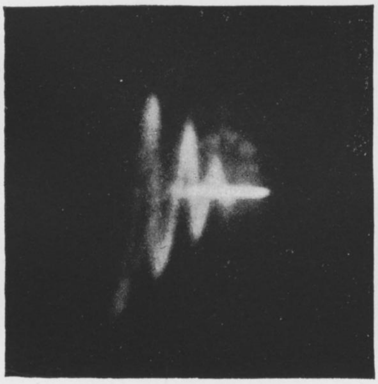

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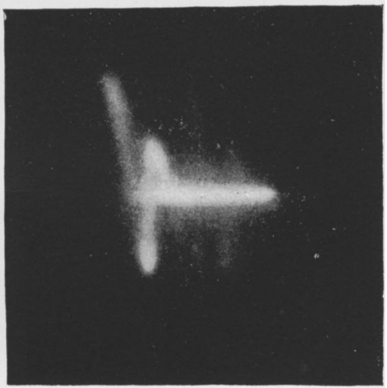

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